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A LARGE CONTAINMENT CAPSULE FOR NUCLEAR REACTOR IRRADIATION OF EXPLOSIVE MATERIALS

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A LARGE CONTAINMENT CAPSULE FOR
NUCLEAR REACTOR IRRADIATION OF
EXPLOSIVE MATERIALS

by

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ABSTRACT

T.e design and development of a large explosive
containment capsule for the irradiation of up to 80
grams of explosive materials is described. The capsule
will fully protect its surroundings, e.g., the core of
a nuclear reactor, if its explosive content detonates.
The minimum safety factor of two was used. The capsule
contains provisions for the containment of gases pro-
duced by detonation or burning of the explosive mate-
rial and the minimizing of any shock wave propagated
outside the capsule. Also, provisions are made to
monitor pressure or gas evolution and the temperature
of the test material during irradiation. Dynamic
pressure pulse and stress-strain measurement tests
were conducted and are described. Analytical calcula-
tions were made for comparison with experimental data,
first to determine the validity of the calculations
and then to obtain information on configurations not
actually tested.

FOREWORD

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INTRODUCTION

The study of effects of reactor irradiations on
explosives was initiated in the nineteen fifties. At
that time it became apparent that the safest way to
irradiate explosives was in a container that would
completely protect the surroundings if a detonation
occurred. The specific requirement for the design and
development of an explosive container that would con-
tain relatively large amounts of explosives for irra-
diation in a nuclear reactor became mandatory, in 1962,
to implement the NERVA Program conducted by the NASA
Space Nuclear Propulsion Office in Cleveland. At that
time Aerojet-General Corporation and Picatinny Arsenal
initiated a program to study the effect of radiation on
explosives, utilizing the General Electric Test Reactor
at Vallecitos Atomic Laboratory, Pleasanton, California.
Picatinny Arsenal was given the responsibility to de-
sign and develop a large explosive capsule for reactor
irradiations. This was a continuation of an earlier
program in which a broad range of materials and geom-
etries for explosive containers were investigated.

OBJECTIVE AND SCOPE

The objective of the work described in this report
was to design a capsule that would enable 80 grams of
explosives to be irradiated safely in a nuclear reactor.
The container design was intended to incorporate such
safety features that any internal dynamic impulse re-
sulting from an explosion would not unduly affect the
immediate surroundings, i.e., the nuclear reactor.

The study was divided into two phases. The first
phase was an empirical determination of the ability of
various metal cylinders to contain the detonation of
explosive charges. The cylinders were fabricated from
steel, lead, and different aluminum alloys. Numerous
combinations of length to diameter for a range of wall
thicknesses were employed. The tests were conducted
by mounting the cylinders vertically on a steel plate
and topping them with another steel plate weighed down
by a 500-pound lead block. Uncased, spherical explosive
charges were mounted at the geometric center and deto-
nated along the cylindrical axis. An empirical expres-
sion was obtained relating the cylinder length, diameter,

wall thickness, and material to the maximum explosive
charge satisfying the containment criterion. Incident-
ally, the criterion used was the ability of the cylinder
to withstand the detonation of the explosive charge
without any rupture occurring. This phase of the work
was described by Mackenzie et al. (Ref 1, 2, and 3).

The second phase was the design and testing of a
series of capsules. The final design successfully met
the reactor safety and engineering requirements.

To grasp the scope of the problem more fully it
should be noted that from all published reports on
irradiation of explosives the amounts irradiated were
very small (1 to 5 grams). As an example, Aerojet-
General Corporation conducted a parallel program for a
small capsule 2 1/8 inches in diameter by 9 inches in
overall length to safely contain 1.8 grams of explo-
sives during reactor irradiation (Ref 4) as compared
to 10.5 inches in diameter by 36.5 inches in length for
an 80-gram sample. For a weight ratio of over 40:1 a
volume ratio of 100:1 had to be realized finally for
the safe operation.

The detonation of an explosive in an explosive
capsule occurs in the following way: First the explo-
sive is in the form of a sphere in a thin aluminum cas-
ing. After initiation the detonation front propagates
through the charge with a velocity characteristic of
the explosive used. In this case the velocity obtained
is about 8000 meters per second, with the pressure be-
hind the front approximately 200 kilobars. Almost
instantaneously the solid explosive is transformed into
a gaseous fireball. Its volume is increased slightly,
its temperature is 3000°C, and its internal pressure
is near 50,000 atmospheres (Ref 5). The fireball is
confined by the spherical casing for 2-3 microseconds,
until the casing is vaporized. The shock wave and the
blast pressure generated by the gases released from
the explosive charge produce the destructive forces.

In other words, the detonating explosive propa-
gates a pressure wave of finite amplitude into the
surrounding medium. The shape of the pressure wave
changes and, particularly in air, the pressure front
becomes steeper and steeper until limited only by

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viscosity and heat conduction. When the propagation velocity disturbance is greater than the velocity of sound in the undisturbed medium, as it usually is, the disturbance is called a shock wave.

After the shock wave propagates through the air and strikes the internal wall of the capsule the wall is instantaneously accelerated. The impulse in the shock point initially consisted of about half of the energy released. Since the response time of the wall is large relative to the duration of the shock wave the effect is practically instantaneous. Sections of the wall nearest the charge acquire the largest velocity and undergo the greatest deformation. The inertia and tensile strength of the capsule resist the impulse during the acceleration of the wall, and, unless rupture occurs, will be brought to rest by the tensile constraints.

The hot explosion gases behind the shock wave are confined by the capsule. The resultant internal blast pressure, in contrast to the short duration of the shock wave pressure, is a function of the total volume of the capsule and the ability of the entire system to act as a heat sink for the gases. Distortion of the capsule wall by the shock wave precedes the arrival of the blast pressure, and the total volume available to the explosion gases is the initial volume plus the enlargement caused by the shock. This is the same situation described by Wise and Proctor (Ref 6). However, their model contained water instead of air in order to simulate an excursion within a nuclear reactor.

The above describes an expanding detonation and how it interacts with the wall of the confining cylinder. To be considered also for the shock effects on an overall basis are the capsule length, reflections from the walls and ends when capped, repeated reflections with decreasing amplitudes, and the elastic-plastic properties of the container when subjected to dynamic loads.

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DESIGN AND DEVELOPMENT

Based on the considerations discussed in the previous section the following param cers were considered in the design of the irradiation capsule:

1. The type of material, size, geometry, and constraints required to attain confinement.

2. The amplitude and time duration of the shock wave incident upon the container wall. This will depend upon the medium surrounding the explosive charge.

3. The dynamic tensile strength and inertia of the wall, including a determination of the deformation or nonspallation limits in the elastic-plastic range.

4. The capability of the capsule to act as a heat sink.

The plastic response of a blast-loaded wall depends on the following: The inertia of the wall, which is a function of its mass. The mass stays fixed but the acceleration depends on the intensity of the shock wave and the dynamic properties of the wall. These dynamic properties in turn depend on the static strength of the wall. The gross strain, which is the final deformation, is influenced by the strain rate, which is high, and the shock wave intensity (Ref 6).

The design criteria include these conditions:

1. The capsule must be completely compatible with the nuclear reactor environment.

2. A capsule used to irradiate 80 grams must completely contain a detonation produced by 160 grams, i.e., twice the material to be irradiated. This might be called a safety factor of two. In actual fact it is greater than two.

3. A maximum capsule diameter of 10 1/2 inches for insertion in the water-filled reactor irradiation facility.

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These conditions affected the geometry of the cap-
sule and the nature of the material to be used. The
mechanical requirements, plus the condition that the
capsule must not acquire excessive amounts of long-lived
radioactivity during irradiation, led to the selection
of 6061-T6 aluminum as the material for the explosive
containment irradiation capsule. In addition to the
radioactivity requirements it was necessary that the
capsule transmit the neutron flux without attenuation
and retain its strength after irradiations.

A right-cylindrical geometry was based upon the
data obtained in the initial phase of the program by
Mackenzie (Ref 3). The relationships between the
cylindrical parameters and the explosive charge weight
led to an equation of the form

$$m = ct^k d^b \qquad (1)$$

Using the 6061-T6 aluminum data from the family of
curves for various wall thicknesses (Fig 2):

$$m = 15.5 \ t^{1.33} \ d^{1.78} \qquad (2)$$

where

      m = maximum amount of explosive, grams
      t = wall thickness, inches
      d = inside diameter, inches

The effects of irradiation upon the mechanical prop-
erties of 6061-T6 aluminum alloy, with exposures to 10^{21}
nvt, increased the ultimate tensile strength 10%, yield
strength 7%, and the elongation 5% (Ref 7). In a cry-
ogenic atmosphere—irradiated at liquid hydrogen (LH)
and tested at LH temperatures—to a total dose of
6×10^{16} nvt, small changes in the mechanical properties
of 6061-T6 aluminum were noted (Ref 8).

All of the testing in this program employed the
explosive Composition C4 (91% RDX, 9% binder). Its high
explosive power (130% TNT) insured that the tested cap-
sule could be used for most explosives.

In addition to the above the following had to be considered in arriving at the final design:

1. Simplicity.

2. Insertion into and removal from the reactor radiation facility in a minimum time without unduly affecting the reactor.

3. The ability to use any combination of sample sizes consistent with the maximum mass requirement.

4. The ability to remove the specimen after irradiation without destroying the container.

5. Sufficient container integrity after an explosion to permit the controlled release of gaseous products.

6. Provisions for monitoring the temperature and pressure.

7. The pressure pulse emitted must be below a level that would produce adverse effects on the surroundings.

8. The ability of the container wall to contain any fragments formed by the detonation of the explosive holder.

The overall length of the container was determined by the reflected shock waves and the volume of expanding gases. Earlier tests showed that the cylinders bulged in the middle and flared out at the ends when subjected to a detonation from a mass of explosive just below the amounts required to cause fragmentation. If the length-to-inside-diameter ratio (L/D) exceeds 6 the flaring does not occur. Below 6 the flaring could be eliminated by shrinking a support or reinforcement ring on each end and adding a closure plug or cap. The L/D ratio of the final design is 4.25. Specific testing on various threads led to the selection of the buttress-type threads for the final design.

The flaring of the ends was probably due to the compression stress, which was approximately doubled by reflection at the ends of the cylinder.

The gas pressure buildup inside the cylinder by the detonation of the explosive can be estimated. Assume that the volume of gas produced will be approximately the same for most explosives of the same weight. Thus 160 grams of Composition C-4 will produce 7.87 moles of gas, computed from the known chemical composition of C-4. If the cylinder is 6 inches in diameter and 36 inches long and the maximum effective temperature is assumed to be $3000°K$, the maximum pressure is approximately 2000 psi (Ref 9).

The physical geometry or volume of the capsule also was used to evaluate the void effect which would be present in the nuclear reactor operations by the insertion and removal of the capsule. The applicable safety rules for the General Electric Test Reactor at the Vallecitos Nuclear Center (Ref 10) indicate that movable experiments, such as the capsule, should not, upon insertion, produce a change in reactivity greater than 2×10^{-5} $\Delta k/k/sec$ or a maximum reactivity effect of 0.002 $\Delta k/k$ from full in to the fully retracted position. From the calculations furnished the resultant off-gas from leakage of a detonated capsule should result in an overall reactivity effect of less than 0.002 $\Delta k/k$.

In order to sufficiently attenuate the shock wave or pressure pulse produced by a maximum explosion, an annular space was provided between the main chamber and the external container, i.e., the capsule had a double wall. The spacing between the walls was larger than the maximum bulge in the preliminary tests. Expansions ranging from 8-10% occurred in the 6061-T6 aluminum tubes. If the explosive weight was halved the deformation was less than 2%. Connections through the outer tube into the annular chamber were made with flexible stainless steel tubing so that pressure monitors or controllers could be used. For shock attenuation purposes a space was also provided at each end (Fig 3).
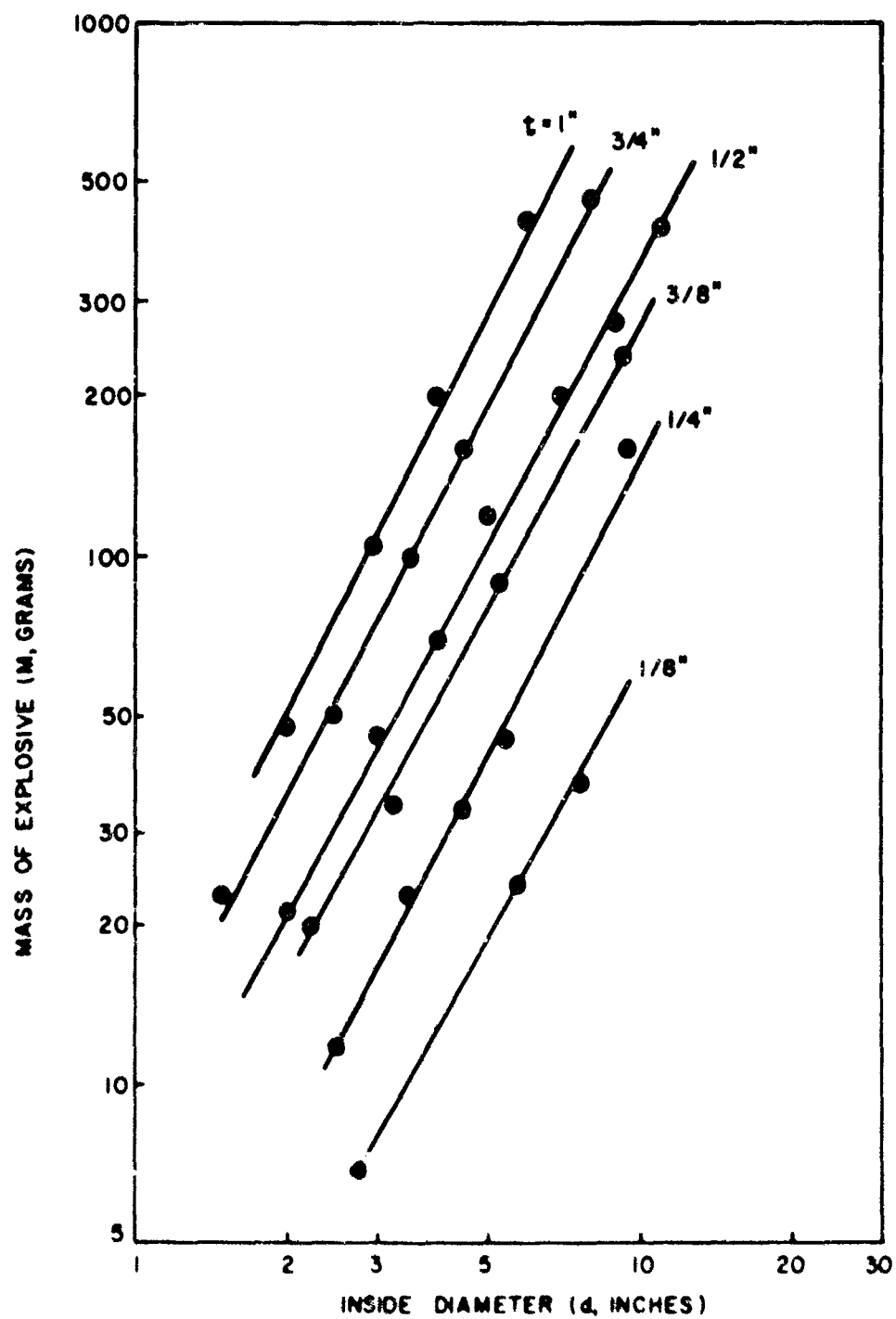
Fig 1   Maximum contained quantity of explosive
as a function of inside diameter (d) and
wall thickness (t):   6061-T1 aluminum

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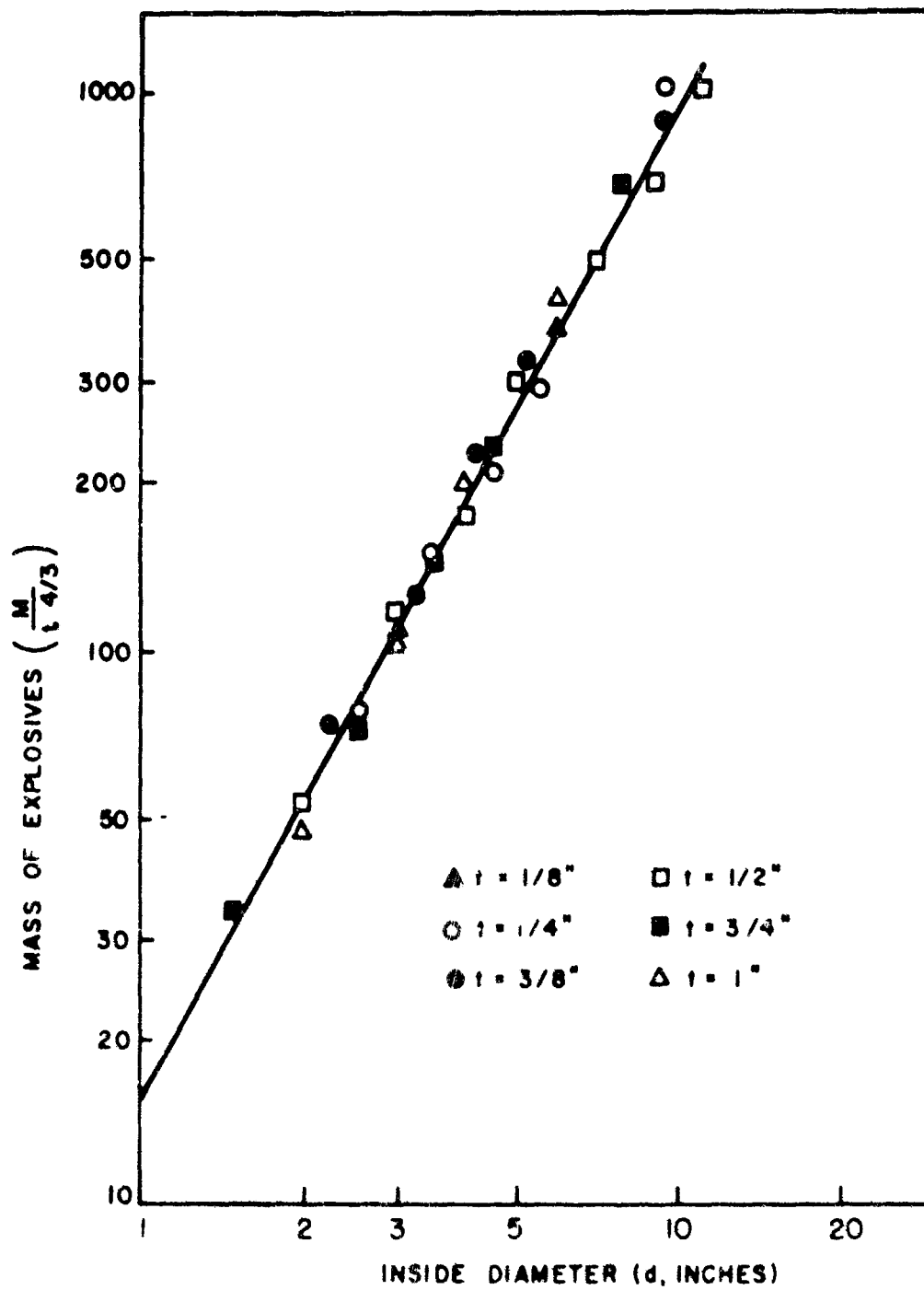
Fig 2   Agreement of data with equation
         m = 15.5 t⁴/³ d¹·⁵

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END RING
ALIGNMENT RING
FLEXIBLE INERT
PRESSURE SUPPLY
THERMOCOUPLE TUBE
COMAX CONNECTOR
END PLUG
THREADED PLUG
OVERALL LENGTH ~ 13.5"
INNER TUBE
SAMPLE HOLDER
GLASS SEAL
HELIUM SUPPLY LINE
SAMPLE HOLDER SUPPORT
SAMPLE CENTERING RING
COMAX CONNECTOR
HELIUM FILLED ANNULUS
OUTER TUBE
MAIN CHAMBER
10.5" DIA
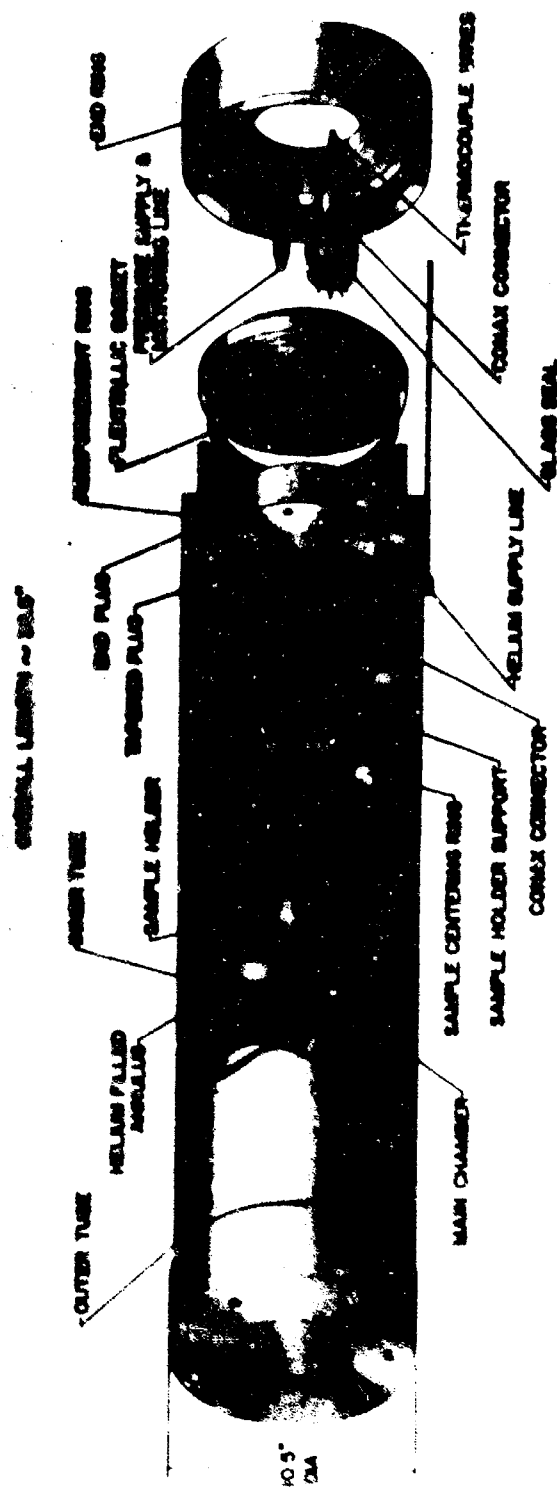
Fig 3   Exploded view of explosive container for reactor irradiation

Fig 3a   Explosive containment capsule assembly
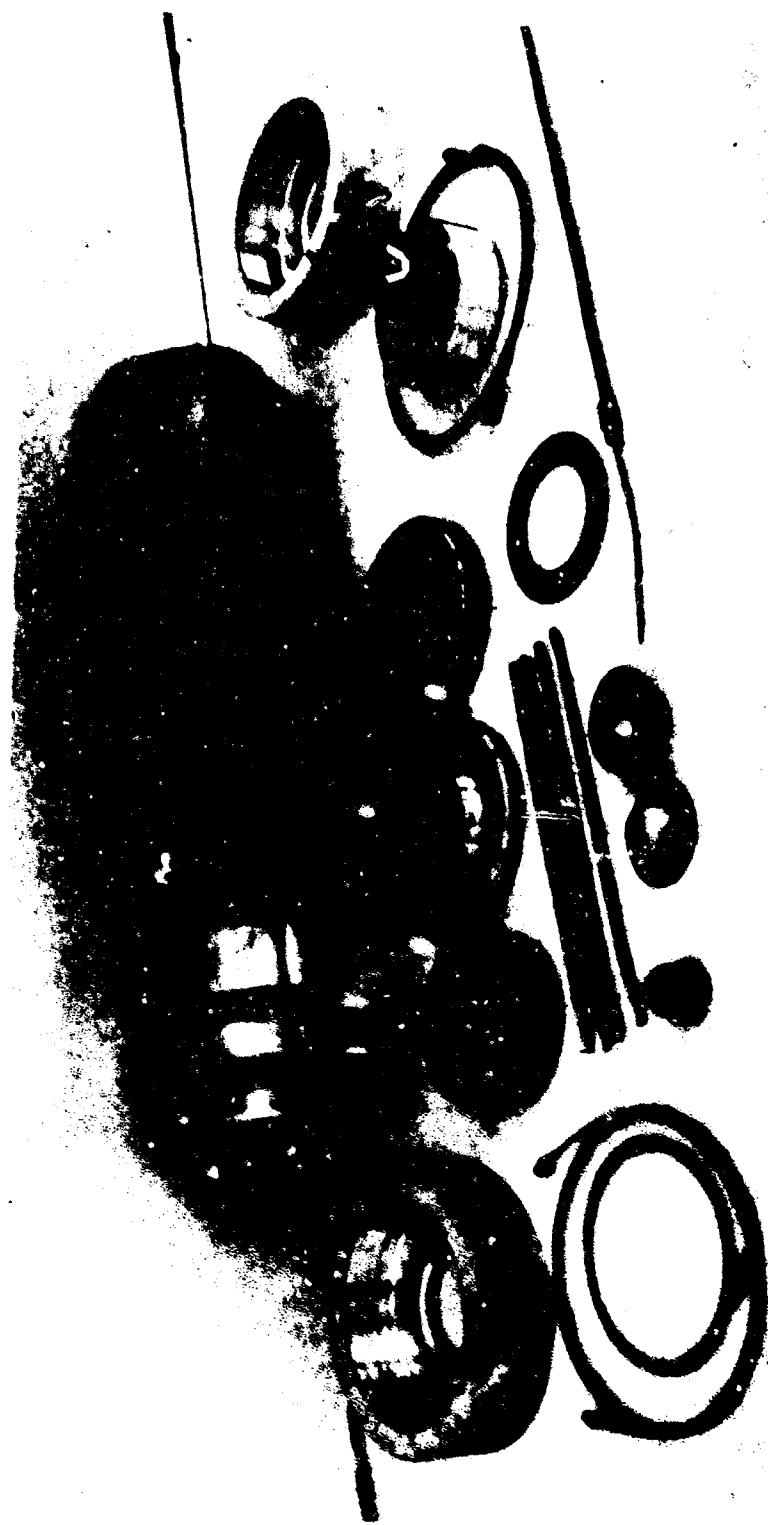
Fig 3b   Explosive containment capsule

The explosive with the thermocouples and flux
wires is held with a spherical holder composed of two
aluminum hemispheres .025 inch thick positioned in
place by four support rods mounted on one of the inner
plugs. The thermocouples will measure the temperatures
at different locations in the explosive sphere while
the flux wires will provide means to determine the ra-
diation level to which the material will be exposed.
The explosive charge holder assembly was designed so
that in case of a detonation only a minimum shock would
be transmitted to the rest of the capsule. In case of
an accidental drop a spacer was added to minimize the
deflection so that the explosive sphere will not be too
close to the wall if a detonation occurs. A complete
set of detailed drawings of the explosive containment
irradiation capsule is included as Appendix I.

Consistent with the philosophy of "maximum cred-
ible accident" which the nuclear reactor industry has
followed, added specifications were placed upon the
design of the explosive containment irradiation capsule:

1. The direction of detonation was changed from
central initiation or along the axis (axisymmetric) to
lateral initiation (asymmetric) so that the detonation
was across the diameter of the explosive charge, and
perpendicular to the cylindrical axis. In all testing
the detonations were directed towards the wall nearest
to the explosive charge.

2. Drop tests were conducted from a height of
at least 10 feet

3. Since the capsule was to be located 1 4 inch
away from the reactor vessel wall in order to obtain
the maximum flux, all stress strain and pressure pulses
were measured on the capsule and the reactor components
at that location.

The purpose of these added requirements was to
eliminate all possible safety and operational hazards
that may occur during transportation and irradiation.
With these built-in features the design of the capsule
could withstand any internal experimental failures—the
worst being a detonation—without affecting, or leading
to the direct failure of, any nearby experiment or re-
actor fuel element that may hinder or interfere with
any reactor operations.

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EXPERIMENTAL INVESTIGATIONS

These additional engineered safeguard specifica-
tions had a definite effect on the design of the system.
The relationships derived by Mackenzie (Ref 3) were no
longer applicable for the specific charge weights due
to the confinement of the explosive and the change in
the direction of detonation.

Knowing the maximum expansion or deformation be-
fore rupture of 6061-T6 aluminum tubes of different
diameters and wall thicknesses enabled the investiga-
tors to select the maximum permissible diameter and
wall thickness and still allow for the annular space.
The measurements selected were 8-inch OD, 6-inch ID,
and 1-inch wall thickness.

Mackenzie's relationship for 6061-T6 aluminum
(Eq 2) predicted that the 6-inch-ID tube with a 1-inch
wall thickness would withstand 378 grams of uncased
Composition C-4 explosive detonated along the axis.
Experimentally, up to 425 grams have been contained in
cylinders of the same size. With the .025-inch-thick
spherical aluminum casing and the direction of detona-
tion changed 90°, the maximum explosive charge of C-4
that can be contained in an 8-inch-OD, 1-inch-thick
6061-T6 aluminum cylinder is 170 grams, or 45% of the
predicted value.

The possibility of missiles being formed upon the
detonation of the explosive in the thin spherical holder
and penetration being effected through the wall was in-
vestigated. High-speed photography indicates that the
thin shell-like casing either vaporizes or breaks up
into minute pieces. Although a momentary confinement
was noted no penetrations occurred through the capsule
wall for the dimensions selected (Fig 6) in any of the
tests.

The purpose of changing the direction of detona-
tion from central initiation to a point on the surface
in the direction across the diameter of the explosive
sphere perpendicular to the axis of the capsule was to
simulate the point of detonation that would have the
worst possible effect. The most literal assumption
was made that a fast reaction occurs on the surface at

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a point on the diameter perpendicular to the axis,
develops into a high-order detonation, and propagates
across the diameter. This stringent test requirement
adds an additional safety factor which is very conser-
vative. It can be visualized as an explosive sphere
whose radius is equal to the diameter of the actual
explosive being centrally initiated without bringing
into account the orientation.

For instrumentation purposes special multiple-lead
Conax connectors[1] designed to withstand static pressures
up to 10,000 psi were incorporated in the container de-
sign to provide a leak-proof leadthrough for the thermo-
couple leads. Tests conducted on these Conax connectors
in similar capsules indicate that they can easily with-
stand the detonation of 160 grams of explosive. A Conax
connector is also installed on the inside of the inner
plug, where the explosive charge holder with the spacer
assembly is mounted. The thermocouple leads from the
explosive holder go through the Conax connector in the
inner plug, then on through a glass-to-metal seal in
the outer end cap. From the seal the leads go through
another Conax connector which serves as a back-up of
the glass-to-metal seal in case of leakage due to hot,
corrosive gases caused by a detonation. A flexible
5/16-inch aluminum tubing of required length encasing
the leads is connected from the Conax connector to a
recorder. For pressure or gas release measurements
the method developed by Aerojet-General Corporation for
its small capsule was used (Ref 1). Penetrations of
1/32 inch were made in both the inner and outer end
plugs. A 1/8-inch stainless steel tubing from a pres-
sure supply and monitoring panel is fitted on the outer
end plug with an adapter. On the inside of the inner
plug the penetration widens into a conical recess for
a tapered plug suspended in an offset position backed
by a steel spacer. By maintaining a constant pressure
the differential can be measured when gases are evolved
during irradiation. If a detonation occurs the shock
wave would drive the plug into the recess, sealing off
the pinhole.

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[1] Conax Corporation, Buffalo, New York

Experimentally it has been shown that after detonation the gases will eventually leak through the pressure-measuring line. To compensate for this a large gas collection tank was installed as part of the system, which was designed to include a rupture disc in the pressure measuring line. Upon rupturing the disc the gases would vent into a large gas collection tank (Fig 4). A filter installed in the pressure-monitoring line will prevent radioactive particles from contaminating the measuring apparatus. This controlled method of gas release is in a closed system but, as stated previously, the "top hat" exhaust system in the General Electric Test Reactor can handle any leakage into the water environment that would be caused by the escape of any gases in the containment capsule upon detonation.

A series of drop tests were conducted from an arbitrarily selected ten-foot height in order to demonstrate the safety of the explosive containment irradiation capsule during normal handling operations. The purpose was to determine the deflection of the explosive charge holder and the effect of such a deflection on the integrity of the capsule in case of a detonation due to an accidental drop. A single-wall capsule was dropped from the height selected onto a steel plate from three different angles or positions: (a) 0° or perpendicular to the cylindrical axis. (b) 45° to the axis, and (c) 90° parallel to the axis, or flat on its side. Preliminary drop tests were conducted with an explosive charge of 160 grams in a holder of spherical diameter of 2 7/16 inches, with a flange giving an overall diameter of 3 1/2 inches. The condition considered most drastic if a drop occurred was the complete shearing of the explosive holder from the support rods and the detonation of the explosive upon contact with the inner wall. Tests indicated that the worst case occurred when the capsule was dropped flat on its side or parallel to the axis and the flange of the holder in line with the impact. Although the explosive holder did not shear off from the support rods in any of the tests, the force of the impact of the drop caused a deflection so great that the explosive charge holder hit the wall of the capsule but without causing a detonation. This gave rise to the question of how close to the wall a charge could be detonated with containment or integrity still being maintained.

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30" (approx. panel height)

30" (approx. panel width)

EVACUATED VENT TANK

HELIUM ← HELIUM

EXHAUST

CAPSULE CONNECT
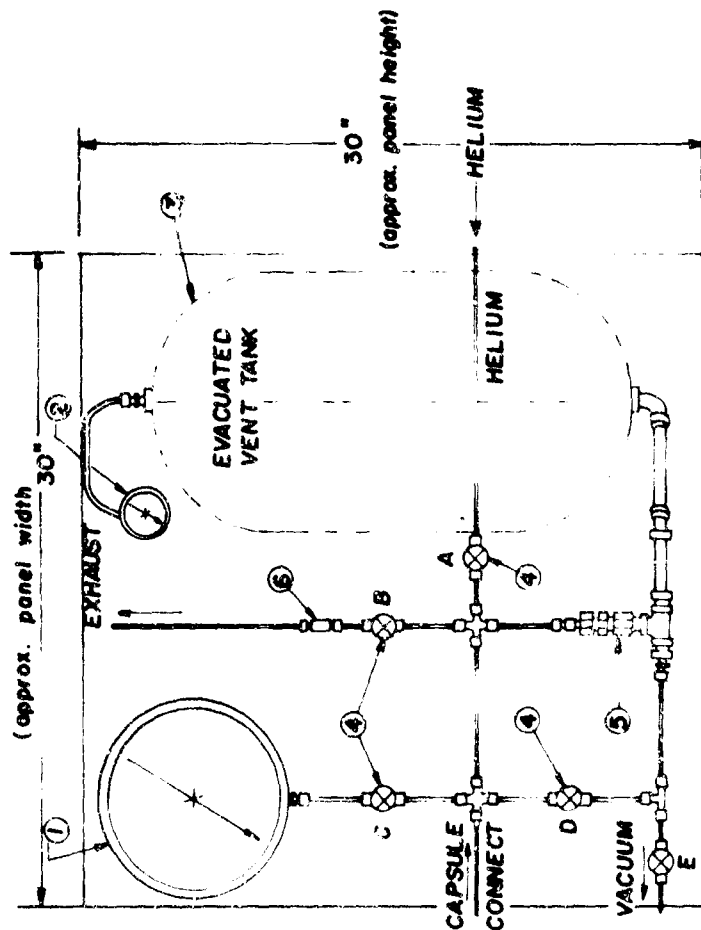
VACUUM

QUANTITY		DESCRIPTION
1	1	PRESSURE GAUGE, HEISE 0-100 psi, 8-1/2" DIAL, .2 psi per DIVISION, 1/5 SUBDIVIDED, WITH REMOTE 5K POTENTIOMETER, 316 s.s. TUBE.
2	1	VACUUM GAUGE, MARSHALLTOWN NO. 228, 2'DIAL SIZE
3	1	VACUUM TANK, 2000 CU. IN., 12 x 24", s.s.
4	5	NEEDLE VALVE, WHITEY NO. OKS 2-316, 1/8" SIZE, s.s. W/SWAGELOK FITTINGS.
5	1	SAFETY HEAD, SCREW TYPE, BLACK, SMALLS & BRYSON ASSY NO. SA-9; s.s.-100 PSIA BURSTING PRESSURE.
6	1	FILTER, NUPRO "F" SERIES INLET FILLER, CAT. NO. SS-2F-7, 5-10 MICRONS s.s.

Fig 4   Pressure measurement panel diagram

Detonation experiments using the designed explosive holder for an 80-gram charge revealed a forbidden zone. Capsule integrity could not be preserved if an 80-gram charge was detonated close to the wall. In a 6-inch-ID, 1-inch-thick 6061-T6 aluminum cylinder, this zone was found to be an annular space 3/4 inch wide from the inner wall in the plane of the explosive charge. This permitted a maximum deflection of 1 3/8 inches from the axis. To prevent a deflection greater than 1 3/8 inches, a spacer or support ring with tie-rods was added to the assembly, thereby eliminating the extended cantilever effect. The location of the spacer placed the fulcrum at about the midpoint of the length of the support rods, thus substantially reducing the amount of deflection. Also the spacer is used as a centering device for the explosive holder for axis alignment (Fig 5). For the 160-gram charge, experiments disclosed that the annular forbidden zone was widened to such a degree that a deflection of more than 3/16 inch from the axis by the explosive sphere was required to produce ruptures. With the spacer assembly installed, tests indicated that this configuration in the capsule could withstand the designated drop of ten feet with a 160-gram weight without excessive deflection or permanent distortion. Also the testing of the detonation of a 160-gram charge with the spacer assembly did not produce any missiles that were able to penetrate the wall of the capsule (Fig 6).

In order to maintain proper alignment within the acceptable limits a quality control feature was incorporated to determine the location of the holder with explosive after assembly and shipment to the specified receiving station at the reactor. X-ray radiographs of the explosive holder area of the capsule would be taken 90° apart soon after arrival at the reactor in order to certify the proper alignment. It was also stipulated that if any accidental drop occurred the capsule would be returned as soon as possible to the loading area for disassembly.
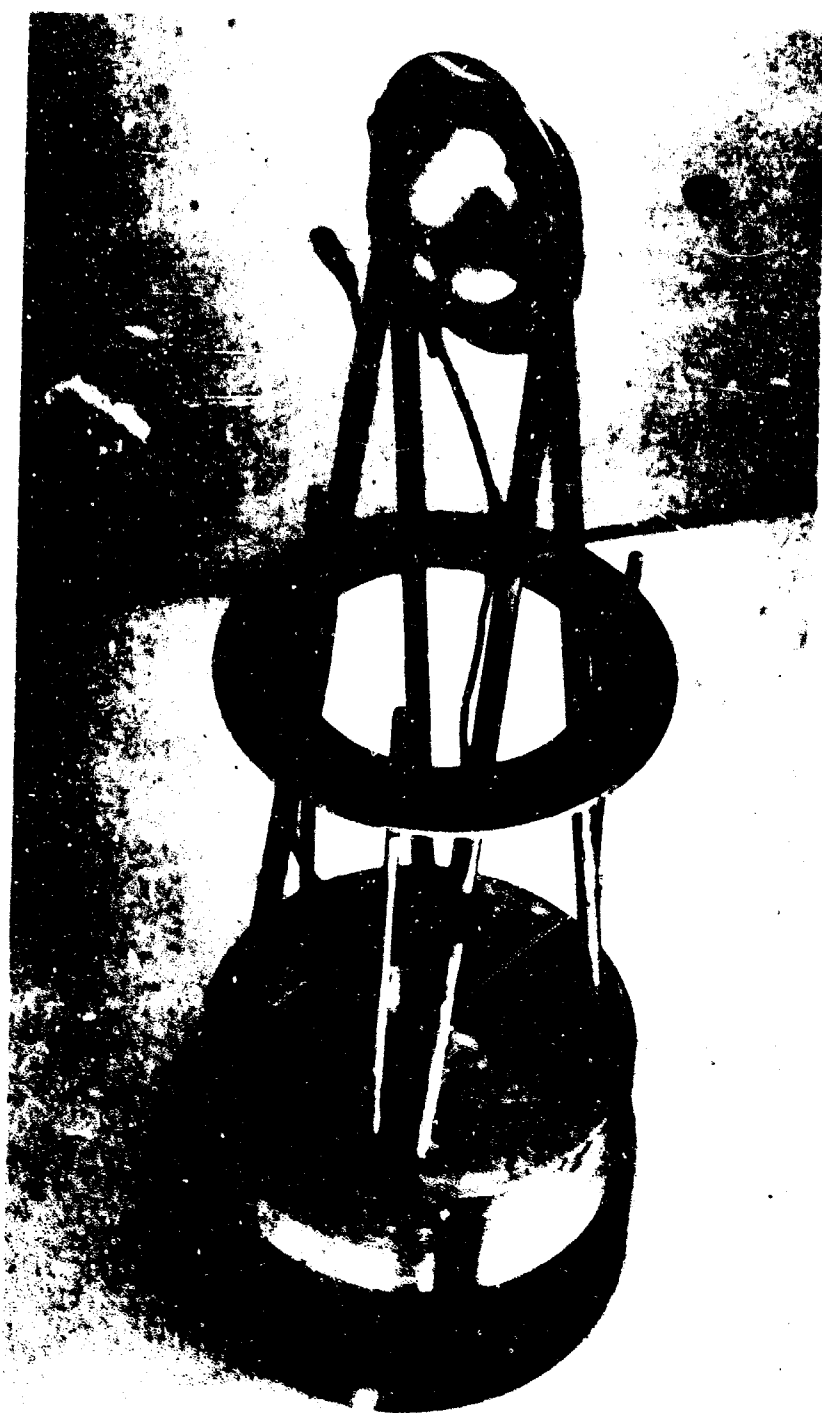
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Figure [...] Explosive [...] cell holder with spacer installed.

Fig 6   Remains of explosive charge holder with spacer assembly
         after detonation of 160 grams of explosive while in capsule

Another modification was incorporated in the containment capsule as an additional engineered safeguard. The original intent had been to have a vacuum in the annular space, which is the principal feature for the attenuation of any shock wave, but the possibility of a leak presented a problem. The filling of the annular space and the rate involved would be noticeable on the pressure-monitoring system but the removal of the capsule was controlled. To eliminate this situation, helium gas at a pressure of 25 psi was used instead of a vacuum. This pressure value was chosen since the pressure at the depth in the water where the containment capsule would be located by the reactor pressure vessel is 20 psi. The positive pressure in the annulus will prevent any water from flowing into that space if a leak develops. This pressure will be monitored continuously with a pressure controller and flow alarm. Any decrease in the pressure will be cause for the immediate removal of the containment capsule. The shock attenuation features will be discussed later.

CONTAINMENT CAPSULE TESTS

A series of tests were conducted to qualify the designed features of the containment capsule. The first four qualification tests were conducted at Picatinny Arsenal and the final four were completed at the Aerojet-General Corporation facility at Downey, California. The main purpose of the investigations, besides verifying the containment and integrity of the capsules, was to measure the stress-strain levels encountered within the containment capsules and the pressure pulses transmitted from the external surfaces at designated locations. Both single-wall and double-wall capsules were tested. The purpose of the single-wall tests was to obtain the stress-strain levels on the inner wall and also the pressure pulse emanating through the inner wall to a point in the air where the outer wall would be located.

Since these types of measurements had been obtained in preliminary tests on an earlier design (Ref 12), Brewer Engineering Laboratories, Inc., Marion, Massachusetts was engaged to make pressure and strain measurements during the qualification tests (Refs 13, 14).

The Picatinny tests included three single-wall and one double-wall capsule. The single-wall capsule assembly consisted of the 8-inch-OD, 6-inch-ID 6061-T6 aluminum cylinder with support rings shrunk fit on the ends and threaded plugs to compare the confinement. These tests were conducted by suspending the single-wall capsule in air (Fig 7) so that stresses, strains, and pressure pulses were measured at specified locations (Fig 8). The pressure transducers were located 1/4 inch away from the capsule while the strain gages were bonded to the capsule at the specified locations.

In the double-wall capsule test at Picatinny, the explosive containment vessel was suspended in water 1/4 inch away from a 1/2-inch-thick aluminum plate simulating the reactor vessel wall. A pressure transducer was located just below the aluminum plate to determine the pressure pulse being transmitted into the space where the inside of the pressure vessel would be located (Fig 9). In the Aerojet series a glass plate was added under the aluminum plate to simulate a beryllium reflector (Fig 10). Instrumentation for these tests consisted of seven pressure transducers adjacent to the capsule surfaces and three strain gages attached to the bottom side of the glass plate (Fig 11).

These tests were to simulate as closely as possible the actual effects resulting from the high-order detonation of 160 grams of C-4 explosive propagating across the diameter of the explosive sphere perpendicular to the cylindrical axis in a double-wall capsule underwater 1/4 inch away from the reactor pressure vessel wall and beryllium reflector. The double-wall capsule was immersed in a glass aquarium with only a few inches clearance between the capsule and the glass sides.

For each of the tests, signals from the pressure transducers and the strain gages were recorded simultaneously on oscilloscope cameras and an FM instrumentation tape recorder (Fig 12). A high-speed framing camera was used to photograph the capsule during detonation. The scopes were activated from the camera and fed in parallel after a delay to a firing unit. This instrumentation is listed in Table 1.
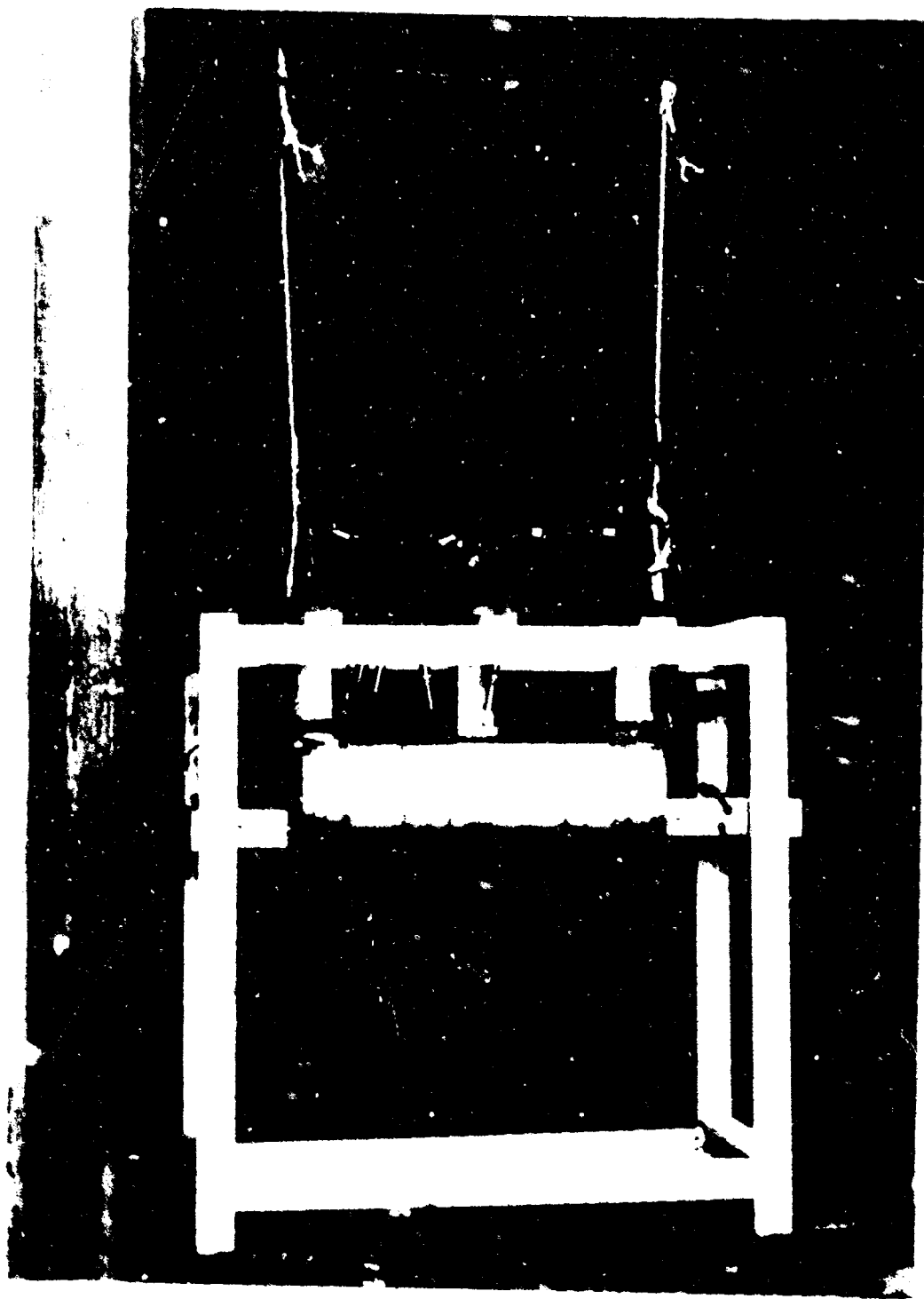
Fig 8 Single-wall capsules. Test schematic showing strain gage and pressure transducer locations
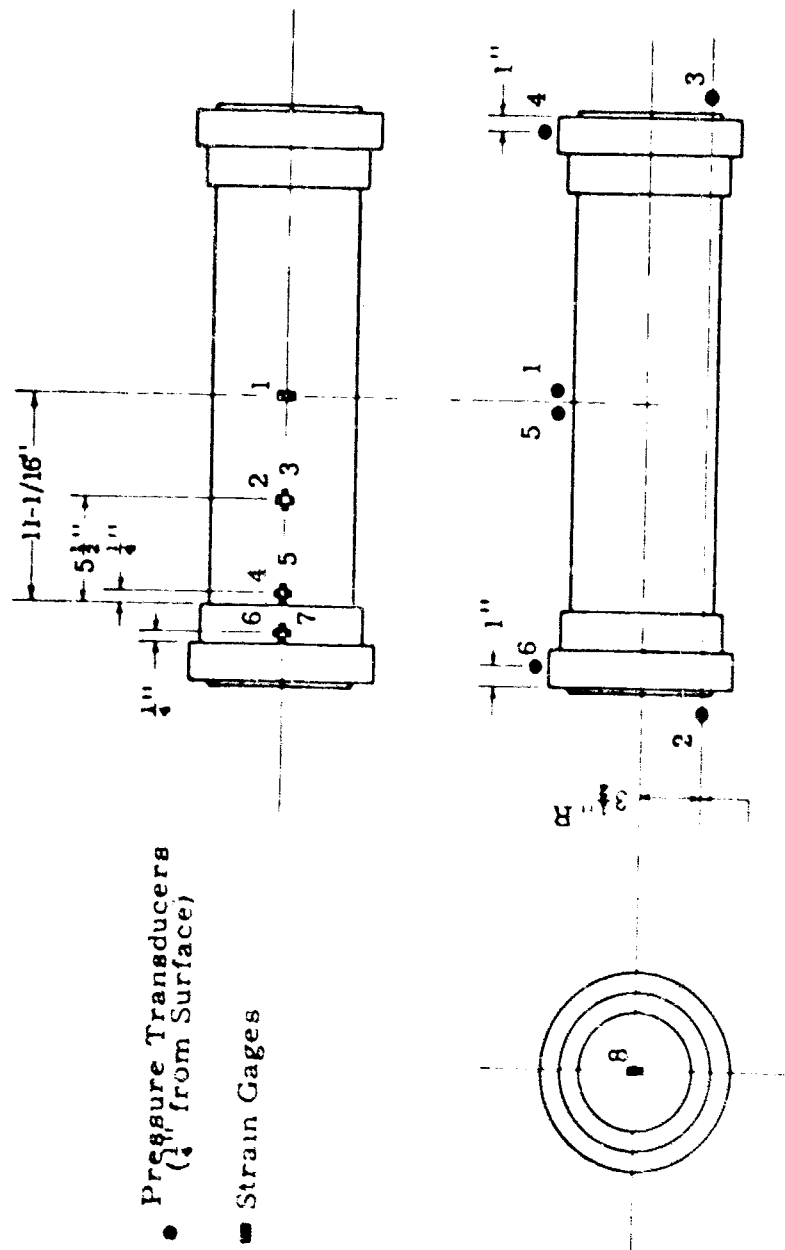
Fig. 4 Double-wall capsule. Test schematic showing strain gage and pressure transducer locations
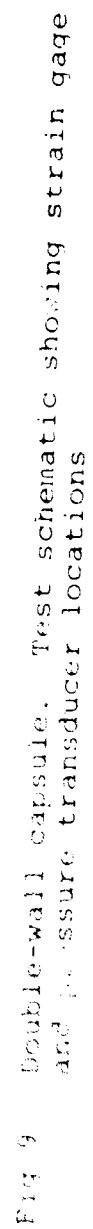
Fig 10   Experimental setup for explosive containment capsules for strain and pressure measurements
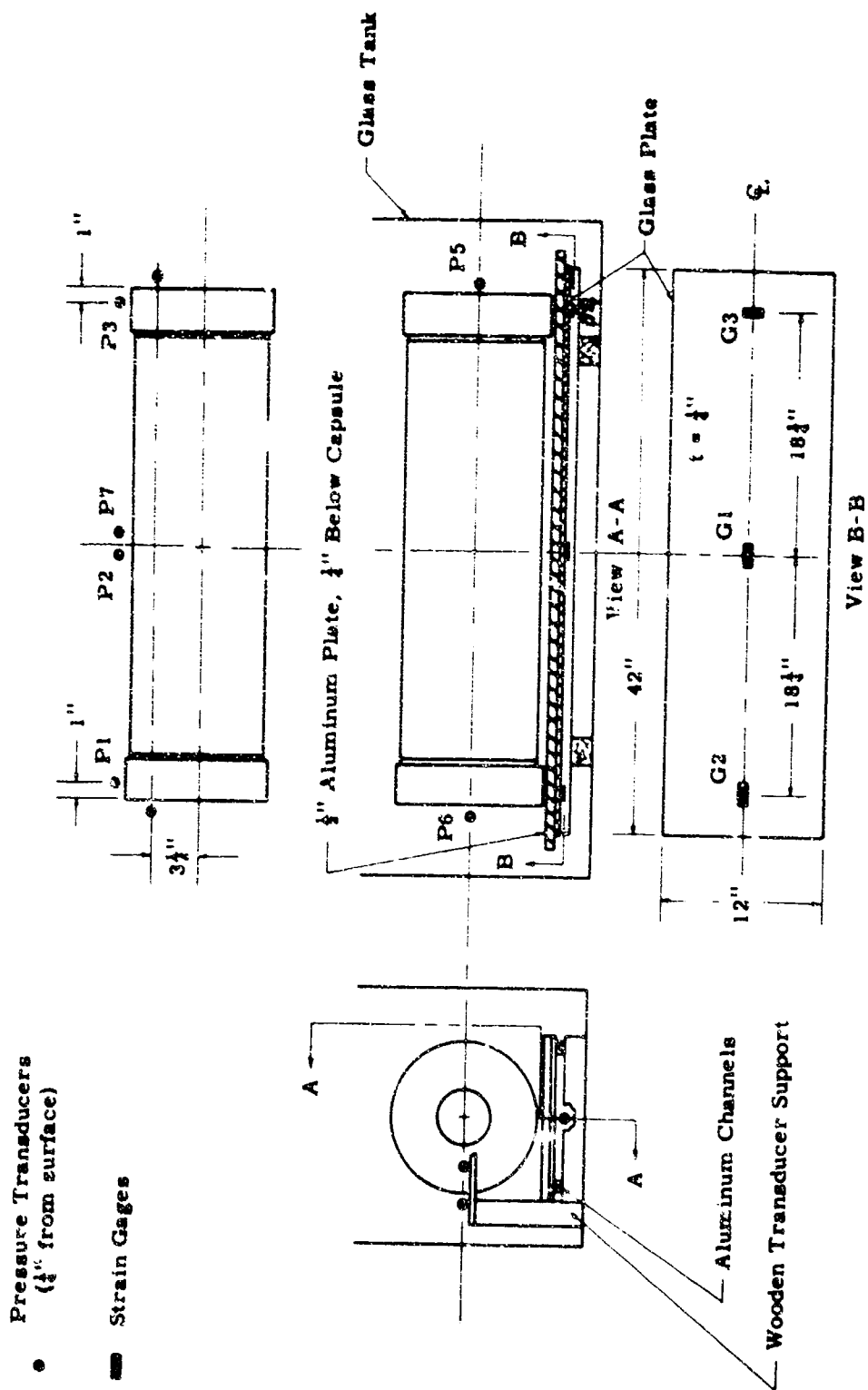
Fig 11 Typical test schematic showing pressure transducers and strain gage locations (Aerojet Series)

27
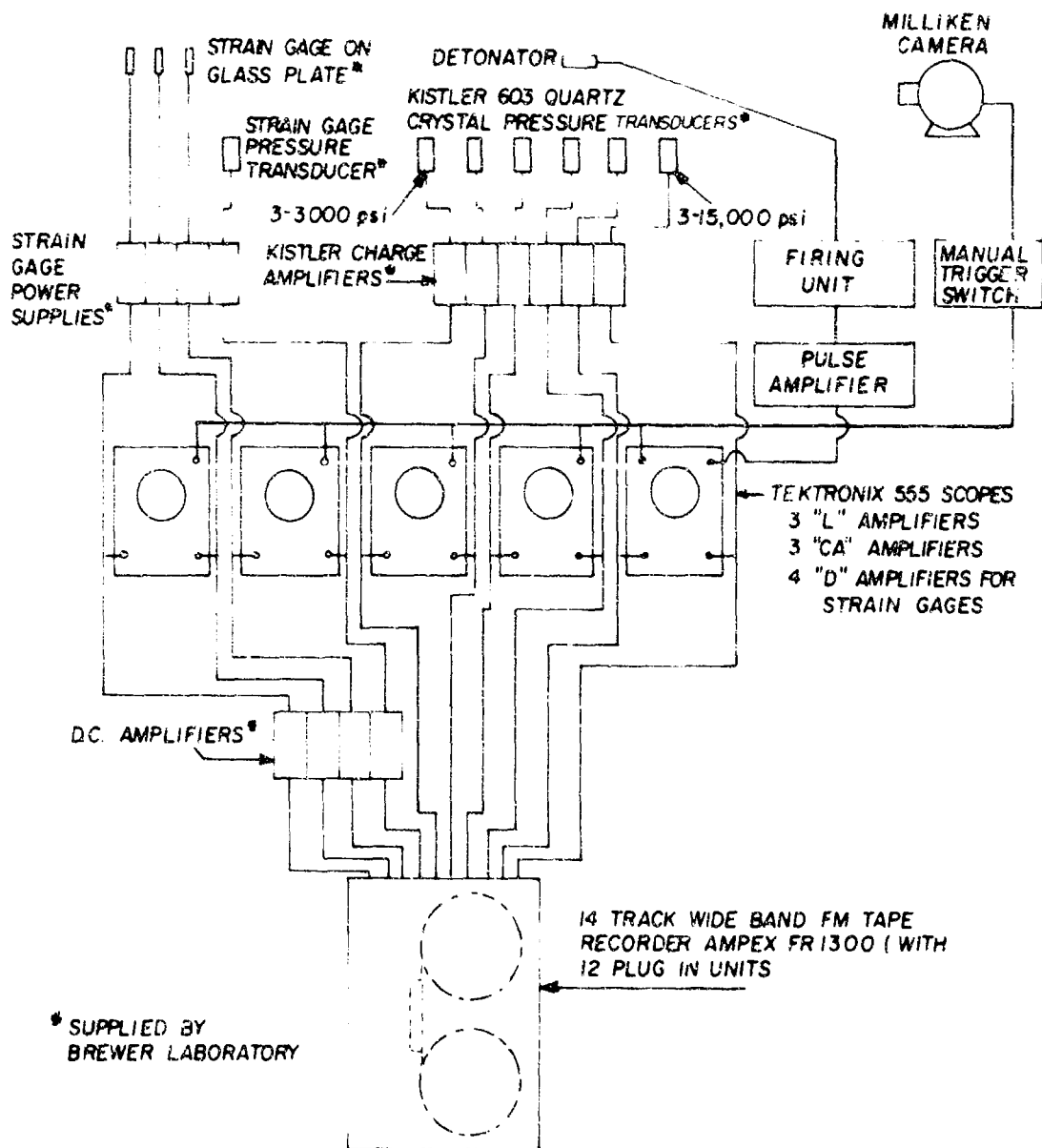
Fig 12   Phase II capsule instrumentation

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TABLE 1

Phase II Explosive Capsule Instrumentation List

A. Pressure transducers
    6 each Kistler quartz crystal pressure transducers
        3   Model 603A, 3000 psi range
        1   Model 603H, 1500 psi range
        2   Model 607A, 60,000 psi range
    1 each Baldwin—Lima—Hamilton bonded strain gage
            Model D-AFM(S), 4000 psi range.

B. Strain gages
    3 each Baldwin—Lima—Hamilton FAB-25-12S6
            Cement: BLH EPY-150 with C-3 overlay
            Waterproofing: RTV-106 (2 coats)

C. Charge amplifiers
    6 each Kistler Model 556

D. D.C. amplifiers
    8 each Dana Lab Models 2000 and 3400

E. Strain gage power supplies, total 4
    System Research Corp., Model 3511-C
    Video Instruments, Model SRB-200

F. 5 each Oscilloscopes - Tektronix, Model 555
        4   Type "D" Pre-amplifier
        3   Type "L" Pre-amplifier
        3   Type "CA" Pre-amplifier

G. 5 each Oscilloscope cameras, Tektronix C-12

H. Tape recorder, Ampex FR-1300

I. Firing unit

    Description, specifications, and operations of this
instrumentation, with the data obtained and data reduc-
tion, are noted in References 13, 14, and 15. The above
was used in the AGC series with the firing unit supplied
by Aerojet.

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A complete set of the data obtained in both the
Picatinny and Aerojet series is summarized in Table 2.
This is also included in a summary report issued by
Aerojet-General Corporation (Ref 16).

The tests indicated the following:

1.   The stress levels on the outer surfaces of
both single- and double-wall capsules (excluding the
inner vessel for $\pm$ 5 inches from the center line) do
not exceed published yield values when the capsules
are subject to the internal detonation of 160 grams of
C-4. The maximum stress level obtained was 25,600 psi,
which is well below the published minimum tensile
yield stress of 35,000 psi.

2.   Pressures transmitted in air at the center
of a single-wall capsule 0.25 inch away from the sur-
face will not exceed 25 psi due to the internal deto-
nation of 160 grams of C-4. This is the pressure
pulse that would be going through the annular space
onto the inner surface of the outer wall of the con-
tainment capsule.

3.   In the double-wall capsule with 25 psig
helium in the annular space the initial pressure pulse
transmitted by the detonation of a concentrically placed
160-gram charge of C-4 will not exceed 5 psi in the
direction of firing 0.25 inch from the surface of the
capsule in a water medium. Subsequent pressure pulses
are produced by the propagation of elastic stress-waves
from the ends of the capsule. About 150 μsec duration
was noted at the center location (Table 3).

4.   The radially transmitted initial pressure
wave at the ends of the double-wall capsule will not
exceed 50 psi. The axially transmitted initial pres-
sure wave from the ends will not exceed 500 psi.

5.   The pressure transient experienced in water
0.25 inch beneath the beryllium reflector mock-up was
less than 3 psi and the maximum strain levels at the
gage locations or the reflector mock-up did not exceed
$\pm$ 70 μin./in.

TABLE 2

Summary of Phase II Capsule Qualification Test

Test No.	Date Test Fired	Basic Type of Capsule	Media Tested in	Media & Pressure in Capsule Annulus	Media & Pressure in Capsule Interior	Type of Sealing 'Veer Plug	Gasket & Plug Installation	Type of Sample Support	Types of Outer Thermocouple Wire Lead thru Seal	Average Gasket Compression	Number of Gauges Strain	Pressure	Peak Pressures & Time After Detonation
PA #1	3/14/66	Single Wall #1-1791	Air	N/A	Air @ Atmospheric		Dry	4-rod Cantilever	N/A	N/A	3	1	#1 center radial 12.5 ps @ 55 µsec
PA #2	3/16/66	Single Wall #1-1792	Air	N/A	Air @ Atmospheric		Dry	4-rod Cantilever	N/A	N/A	8	6	#1 & 2 center radial 17.5 psi #4 center radial 5 ps
PA #3	3/17/66	Single Wall #1-1793	Air	N/A	Air @ Atmospheric		Dry	4-rod Cantilever	N/A	N/A	8	6	#1 center radial 11 psi initial pulse 15.5 ps @ 5 µsec
PA #4	3/18/66	Double Wall P-155371	Water	Helium @ 25 psig	Helium @ 25 psig	Frustum of Cone	Dry	4-rod Cantilever	Glass-to-Metal	Not Measured	8	6	#1 center radial 5 ps @ 530 µsec > 40 ps @ 530 µsec #2 38 psi @ 350 µsec #3 data lost #4 430 psi @ 400 µsec #5 & 6 48 psi @ 110 µsec
AGC #1	6/7/66	Double Wall S/N 1	Water	Helium @ 25 psig	Helium @ 25 psig	Frustum of Cone	Dry	4-rod Cantilever Support Ring & tie rods	Glass-to-Metal	0.012-0.015 inch	8	7	P1P2 radial center 4.5 ps P3 radial over end 52 ps P5 axial over end 200 ps P4 below glass < 25 ps
AGC #2	6/9/66	Double Wall S/N 3	Water	Helium @ 25 psig	Helium @ 25 psig	Full point Cone	Blue goop on threads of inner plugs & gaskets	4-rod Cantilever Support Ring & tie rods	Conax connector	0.017-0.018 inch	8	7	P1P2 radial center 8 ps P4 radial over end 8 ps P5 axial over end 20 ps P4 below glass < 5 ps
AGC #3	6/10/66	Double Wall S/N 2	Water	Helium @ 25 psig	Helium @ 25 psig	Full point cone with back-up plate	Blue goop on threads of inner plugs & gaskets	4-rod Cantilever Support Ring & tie rods	Conax connector	0.016-0.018 inch	8		P1P2 radial center 8 ps P3 radial over end 95 ps P5 axial over end 25 ps P4 below glass 25 ps
AGC #4	8/3/66	Double Wall (Modified)	Water	Helium @ 25 psig	Helium @ 25 psig	Full point cone with back-up plate	Blue goop on threads of inner plugs & gaskets	4-rod Cantilever Support Ring & tie rods	Conax connector	0.020-0.024 inch	0	0	No measurements made

NOTES
(1) Outer tube of steel in lieu of aluminum
(2) Followed by a pulse of 90 psi of 20 µsec duration
(3) Measured with Calipers
(4) Measured from X-ray

A

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TABLE 2

Phase II Capsule Qualification Test Results

Average Gasket Compression	Number of Gauges Strain	Number of Gauges Pressure	Peak Pressures & Time After Detonation	Stress-Strain Levels	Maximum Inner Tube Expansion		Remarks	Gas Leakage
N A	4	3	#1 center radially 12.5 psi @ 55 μsec	Strain gauges suffered bond failures	~ 20' (~2.5% elong)		Capsule used for drop tests no adverse effects	N A
N A	5	6	#1 & 2 center radially ~17.8 psi / #4 end radially ~5 psi	#2 16 0 " psi / #3 11.500 psi } @ 190 μsec / #4 16.700 psi / #5 25.000 psi ~800 in in sec	~ 20		Capsule ruptured probably due to off-centered charge	N A
N A	8	6	#1 center radially 11 psi / initial pulse 15.5 psi @ 2-3 μsec	#1 3 & 5 failed / #2 25.300 psi } @ 195 μsec / #3 15.600 psi	~ 20'		No cracking of tube.	N A
Not measured	8	6	#1 center radially 5 psi @ 530 μsec > 30 psi @ 530 μsec / #2 38 psi @ 350 μsec / #3 data lost / #4 430 psi @ 300 μsec / #5 & 6 48 psi @ 110 μsec	#8 13.700 psi 910 μin in / #2 360 μin in Strain rate 48 in in sec	Not Measured		Vee-plug sealed gas leaked out around live-end gasket. Jacket pressure increased from 25 to 28 psig. Maximum pressure in live end compartment 11 psig. No tube failure	Not obtained due to gross external jacket leakage
0.12-0.015 inch	3	2	P_2P_7 radially center 4.5 psi / P_3 radially live-end 32 psi / P_5 axially live-end 200 psi / P_4 below glass ~ 0 psi	Not obtained due to electrical interference.	24'(3) Measured parallel to direction of detonation / 29'(4)	16 (3) Measured perpendicular to direction of detonation / 22 (4)	Vee-plug failed to seal gas jet melted solder in glass-to-metal lead wire seal resulting in blowout of aluminum conduit, etc. No tube failure	Repressurized post tests gave 2900 cc min @ 49 psi / 8000 cc min @ 101 psi / 5400 cc min @ 25 psi / 6720 cc min @ 69 psi
0.17-0.018 inch	3	2	P_2P_7 radially center 5.0 psi / P_3 radially live end 8 psi / P_5 axially live-end 170 psi / P_4 below glass < 3 psi	Not obtained due to electrical interference.	19'(4)	35 (4)	Vee-plug sealed good, inner plug @ dead end dislodged. Jacket pressure increased to 37 psig. Small leak at dead end. No tube failure	1880 cc min initially / 29 cc min after 3000 cc released
0.16-0.018 inch	4	-	P_2P_7 radially center 3.5 psi (2) / P_3 radially live end 45 psi / P_5 axially live end 475 psi / P_4 below glass ~ 0 psi	Dead end 53 / Live end 49 / Center 24 Strain in Glass Plate μin in	42 (4)	74 (4)	No gas leakage into water. Slow gas leakage through pressure line 'triggered' rupture disc and gases vented into tank as predicted. No tube failure	0 cc min
0.20-0.024 inch	0	0	No measurements made	No measurements made	27 (3)	15 (3)	Gas leakage through pressure line triggered rupture disc at 95 psi after 60 sec but small capacity filter prevented rapid flow of gas into vent tank so that capsule remained at above and vent tank at below atmospheric pressure after 30 min. No tube failure.	3000 cc min initially / 1900 cc min after 6 minutes / 1600 cc min after 15 min

TABLE 3

Pressure Pulse and Strain Measurements
for Explosive Containment Capsule[a]

Location	Transducer or Gage	Item No.	Test 1	Test 2	Test 3
				psi or μin./in.	
Radial pressure center	A	P2, P7	4.5	5.0[b]	3.5[c]
Radial pressure live end		P3	32	8	45
Radial pressure dead end	B	P1	~45	8	25
Axial pressure live end		P5	200	170	~475[d]
Axial pressure dead end	C	P6	142	116	~400[d]
Pressure beneath glass		P4	~0	~3	~0
Glass plate strain dead end		G2	-	-	53

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Table 3 (continued)

Location	Transducer or Gage	Item No.	Test 1	Test 2 psi or μin./in.	Test 3
live end		G3	–	–	49
center		C1	–	–	24

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aData presented are first pulse only. Positions related to Figure 11. Due to the symmetry of the capsules the readings are grouped under three headings: Position A is at the center, Position B is radially at the ends, and Position C is axially at the ends.
bFollowed by + 25 psi at 125 kc.
cFollowed by 90 psi pulse of 20 μsec duration.
dPulse duration of 12-15 μsec.

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The following observations were made as a result of these investigations:

1. The average permanent diametrical expansion experienced with the 8-inch-OD, 6-inch-ID tube in both type tests ranged from .20 to .58 inch or an elongation from 2.5% to 7.0%. Readings were taken in the line of firing or perpendicular to it, as noted in Table 2 It is interesting to note that the maximum bulging of .74 inch was perpendicular to the line of detonation.

2. Because of the expansion and permanent deformation of the inner tube and the hot gases generated by the detonation of 160 grams of C-4 the pressure in the annular space was noted to increase on each test from the original 25 psi. The maximum value recorded was 37 psi.

3. The strain gages on the center in the single-wall tests did not survive the high strain rates. The maximum rate obtained was about 800 in./in./sec at ± 5 1/2 inches from the center. The maximum in the double-wall tests was 910 in./in./sec, which was recorded on the end of the capsule.

4. It is significant to note that the capsules were not excited into any high-amplitude vibrations at any of their own resonant frequencies. Such a phenomenon would result in a series of repetitive pressure waves into the surrounding water (Ref 14).

5. The shock arrival times (Table 4) at the strain gage and pressure transducer locations in the Picatinny series of tests give an insight into the strain rates experienced by the capsules.

The experience and knowledge obtained from the tests were put to use for the modifications required for appropriate holders to irradiate propellants and detonators. The propellant sample would be enclosed in a cylindrical assembly whose overall volume was based on the amount of explosives (80 grams) in the propellant, excluding binders and inert materials. This would replace the explosive sphere charge holder in the support assembly.

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TABLE 4

Shock Arrival Times

Time, μsec

Strain Gage No.	Pressure Transducer No.	1-1791	1-1792	1-1793	Double-Wall Capsule	Location on Capsule
1		-	28	-	165	Radial in center
2		-	40	-	165	Radial in center
3		-	40	-	~130	Diagonal
4		-	65	-	~120	Diagonal on end
5		-	61	61	118	Diagonal on end
6		-	72	-	~130	Axial on end
7		-	70	-	~130	Axial on end
8		-	92	-	120	Axial on end
	1	44	43	-	-	Under alum plate
	2	-	-	-		Radial in center
	3	-	-	-		Axial on end
	4	-	~85	-	~165	Axial on end
	5	-	-	46	~110	Diagonal on end
	6	-	-	~125	110	Diagonal on end

ᵃAll referenced to detonator firing pulse.
ᵇAll times from oscilloscope photographs except transducer #6, double-wall capsule.

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Table 4 (continued)

c*Time measured from first significant strain on pressure amplitude.
For example, strain amplitude at gages 1 and 2 double-wall capsule,
due to pressure wave is too low to detect.
Time is to elastic stress waves from ends of cylinder.
dLocations of strain gages and pressure transducers referenced to
Figure 9 (Picatinny Series).

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For detonators or igniters the design is a flat rectangular can which will hold about 150 detonators with a total amount of explosive of about 40 grams. The insertion of the capsule into its irradiation position would orient the holder in order to minimize self-shielding and have a uniform radiation flux for the detonators.

A gas-cooling line using helium as a coolant has been designed which enters the capsule end caps, passes through the end plugs and into the sample holder. The return of the helium gas would be through the pressure measurement line used in the noncooled capsules. Assembly and detail drawings showing all these features are in Appendix II.

BEHAVIOR OF THE CAPSULE DURING DETONATION

The problem of trying to understand and explain the events that occur with the detonation of an explosive charge in an explosive containment irradiation capsule with respect to the effects on its surroundings when in a nuclear reactor is divided into three phases: (a) the detonation within the capsule, (b) the effects on the capsule, including dynamic loading, deformation, transmission, and attenuation, and (c) the effect transmitted to the surrounding media due to the pressure pulses emanating from the capsule.

All three aspects have been discussed as far as the experimental results are concerned. Dynamic stress-strain measurement is a difficult problem. The dynamic stress-strain relation is achieved when a solid is subjected to a compressive shock loading. The knowledge of the response of the medium to the loading behavior as well as the unloading behavior would help to solve the problem but few experiments have been reported. The literature on the dynamic characteristics of 6061-T6 aluminum (Refs 17-23) due to shock loading by explosives does not contain much information on the maximum deformation and rate of deformation in cylinders with thickness-to-radius ratios of 4 to 1.

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The technique of Johnson, Stein, and Davis (Ref 21) regarding the dynamic symmetrical expansion of a thin ring closely represents this problem. With that method, dynamic uni-axial stress-strain data can be obtained at high strain rates. This technique was also used by Hoggart et al. (Ref 22) on 6061-T6 aluminum rings expanding symmetrically under the influence of their own inertia. Impulsively loaded to produce high initial radial velocities, the expanding circular rings are decelerated by the radial components of the hoop stresses. The technique excludes the wave propagation which normally occurs when contact between the ring and the core is broken as the tensile wave reflected from the outside surface arrives at the ring-core interface. Strain rate measurements in the range of 10^3 to 10^4 in./in./sec are considered feasible by this method.

The method devised by Fyfe (Ref 23) in which plastic stress waves propagating radially outward were created by exploding a copper wire along the axis was considered applicable for a small sample (4 inches long, 1 1/2 inches outside diameter, 1/4 inch thickness). Whether the experimental setup could be scaled upwards without prohibitive costs could not be determined but if it can then both experimental and theoretical approaches put forth should be investigated further.

The problem on hand is a bit more complicated. Due to the method of testing, it is not known whether the wave propagation and strain hardening effects can be ignored. The thin-walled aluminum spherical casing on the explosive plus the air gap to the wall of the tube may have the same effect as a plate impact shock. Add to this the temperature of the expanding gases and the problem becomes more complex.

The strain-rate sensitivity for 6061-T6 aluminum has been found to be quite small (Refs 17, 23-25), with the dependence becoming more pronounced in the region above 10^4 in./in./sec.

Perrone (Ref 26) has developed a simplified method for solving impulsively loaded structures of rate-sensitive materials. An adequate mathematical description of material behavior for important structural metals is given in the following power law:

$$\frac{\sigma}{\sigma_0} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{n}} \tag{1}$$

where

$\dot{\varepsilon}$ = strain rate
σ_0 = static yield stress (when $\varepsilon = 0$)
σ = dynamic yield stress
D, n = material constants

For cylinders the radial strain ε is defined as

$$\varepsilon = \frac{r - r_0}{r_0} \tag{2}$$

as shown in Figure 13 for symmetrical expansion. For the strain rate

$$\dot{\varepsilon} = \frac{d\varepsilon}{dt} = \frac{1}{r_0} \frac{dr}{dt} = \frac{v}{r_0} = \frac{\dot{r}}{r_0} \tag{3}$$

with $v = \frac{dr}{dt}$

Normally the hoop stress σ can be solved from the equation of motion for a wall element with ρ = mass density, and differentiating (3), substitute in

$$\sigma = -\rho r \ddot{r} \tag{4}$$

or

$$\sigma = -\rho r r_0 \ddot{\varepsilon} \tag{5}$$

to show the hoop stress as a function of the ring deceleration (Ref 21).

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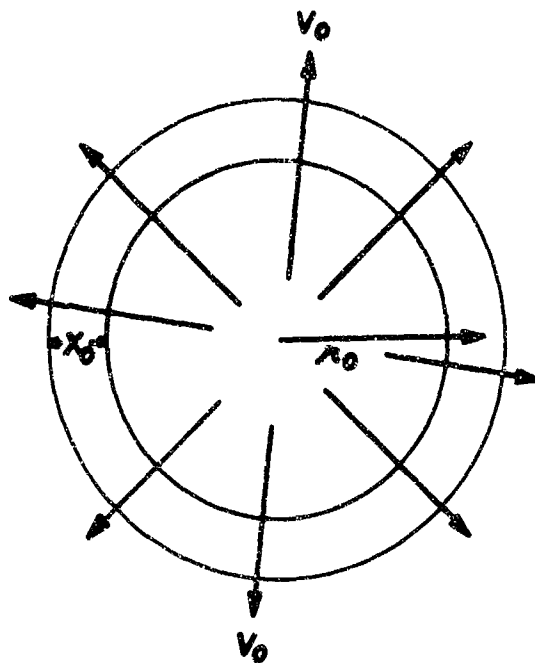
INITIAL CONDITIONS

r_0 = INITIAL MEDIAN RADIUS

V_0 = INITIAL RADIAL VELOCITY

X_0 = INITIAL RING THICKNESS

INSTANTANEOUS CONDITIONS

r = FINAL MEDIAN RADIUS $r > r_0$

V = RADIAL VELOCITY, $\dot{r}$

X = RING THICKNESS $X < X_0$

σ = CIRCUMFERENTIAL STRESS

$\dfrac{V}{r}$ = STRAIN RATE, $\dot{\varepsilon}$

$\sigma = -\rho\, r\, \ddot{r}$

or $\sigma = -\rho\, r\, r_0 \ddot{\varepsilon}$

SYMMETRICAL EXPANSION

Fig 13   The Expanding Ring

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The strain rates obtained in these tests were obtained by using the permanent deformation values in Table 2 and the times obtained for shock arrivals at the different gages as well as photographs taken with a Beckman and Whitley 189 Framing Camera. More reliable data are required but the indications are that where expansions of 2.5% and over were experienced the time intervals show the possibility of strain rates approaching 10,000 in./in./sec. In no case was the ultimate strain of .15 in./in. for 6061-T6 aluminum reached.

Using that strain rate in Equation 1 with the values of $n = 4$ and $D = 6400/sec$ for 6061 aluminum (Ref 23) the dynamic yield stress is determined to be 72,000 psi based on a minimum static stress value of 35,000 psi.

The problem eventually centered on the effects transmitted outside the irradiation capsule to the surrounding media. Although engineered safeguards have been developed, the condition with the worst consequences was the shock wave emanating from the capsule when the annulus was filled with water. Additional data were also required to determine the pulses generated with the detonation of an 80-gram explosive charge under regular operating conditions, i.e., helium at 25 psig in the annular space. Also calculations were to be made to obtain a comparison with the experimental data to determine the accuracy of the method of computation. Time and the need for economy dictated the use of calculations.

In an effort to develop a mathematical model to predict the pressures at specified locations, several approaches were tried. A one-dimensional Lagrangian hydrodynamic code was the first attempt. This was a one-dimensional spherical calculation of the free expansion of a centrally initiated sphere of explosive into a spherical cavity and the subsequent interaction of the gases with a rigid spherical boundary. The equation of state for the detonation products of Composition B was used instead of that for C-4. Air in the cavity and the motion of the wall were neglected. Because of the cylindrical geometry only the initial pressure at the wall was obtained. The result for the peak pressure at the surface of the inner wall was

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30 kilobars for a 160-gram charge. The experimental
data indicate that the value obtained was at least an
order of magnitude too high.

Due to the complexity of the problem, independent
approaches were made by Picatinny Arsenal, Aerojet-
General, and Lawrence Radiation Laboratory.

Three cases were considered to determine the peak
shock pressure transmitted from the capsule under the
conditions noted:

Case I, 80-gram charge of Composition B deto-
nating when the annulus is filled with helium at
25 psig.

Case II, Same as Case I except annulus is filled
with water.

Case III, 160-gram charge of Composition B de-
tonating when the annulus is filled with helium at
25 psig.

Case I simulates the irradiation test conditions
while Case II simulates the condition with the worst
consequences. Case III simulates the actual testing
conditions used in the qualification tests.

Manual calculations were made by this Laboratory
assuming one-dimensional symmetry, a TNT spherical
charge pressure-versus-distance scaling law, and imped-
ance mis-match techniques. This is described in detail
in Appendix III. Figure 14 shows a two-dimensional
model of the capsule, the reactor pressure vessel, and
a beryllium reflector, with the dimensions shown in
inches. A, B, and C are the points at which the pres-
sure pulses were calculated. Figure 15 shows a graphic
presentation of the scaling law taken from the work by
Granström (Refs 27, 28). This work was performed with
TNT; the peak normal reflected overpressure values were
used at the distance related to the explosive charge
where the inner wall was located. At low pressures the
pressure was assumed to be a linear function of the
particle velocity (Ref 29). This method also assumed
no attenuation of the shock; higher pressures than
those measured would be predicted but the relative

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magnitude of the pressure pulses should be correct.
Figure 16 is a graphic presentation of Case II showing
the pressures and velocities relative to time and dis-
tance using the peak pressure value obtained from
Granstrom's curve (Fig 15) and the inside of the inner
chamber as the reference point for the position. The
calculations are compiled in Table 5 along with the
results from Aerojet and LRL.

Aerojet-General used the WUNDY computer code
(Ref 30), which assumes cylindrical geometry (Fig 14)
and no material strength (i.e., that metals behave like
fluids). These assumptions are acceptable with high
pressures but not with the relatively low pressures
generated under the stated conditions. This resulted
in high calculated pressures that were conservative.
The calculations were carried out (Ref 15) in the water-
filled case and, in accordance with the program, the
first peak shock pressures were considered to be the
most accurate since metal motion did not affect the re-
sult. Subsequent pressures and motion are not as ac-
curate so these should be ignored. Since the Picatinny
calculations agreed better with the observed pressures
the remaining cases were not calculated using the WUNDY
code.

The Lawrence Radiation Laboratory (LRL) made one-
dimensional calculations assuming spherical symmetry
and the elastic-plastic version of the K.O. computer
code. Figure 17 depicts the spherical configuration
used as input for these calculations. Since this code
is generally used for higher pressure calculations,
pressures less than 10^{-6} megabars are normally rounded
off. The megabars dimension is due to the high pres-
sure range that the K.O. code normally uses. To deter-
mine the errors that can be expected with this code,
Case III (160 grams with helium in the annulus) was
calculated a second time and rounding off was eliminated,
as shown in Table 6. No permanent deformation of the
inner tube was calculated although expansion did occur
in the tests (Table 2). Also included were the maximum
tensile stresses and the arrival times for the pressure
pulses and tensile stresses.

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TABLE 5

Comparison of Experimental and Calculated Peak
Pressure Pulses (psi) in Water Outside
Containment Capsule

Position Direction	CASE I 80-Gram Charge Helium in Annulus			CASE II 80-Gram Charge Water in Annulus			CASE III 160-Gram Charge Helium in Annulus			CASE IV 160-Gram Charge Water in Annulus
	A Radial	B Axial	C Diagonal	A Radial	B Axial	C Diagonal	A Radial	B Axial	C Diagonal	A Radial
Experimental[a]	2.1 - 3.0	5 - 27	70 - 285	-	-	-	3.5 - 5.0	8 - 45	116 - 475	
Piqation calculations	~0	.370	296	3000	-	296	~0	.600	500	-
Aerojet WUNDY calculations	-	-	-	160,000	-	-	140	-	-	-
LRL K.O. calculations	-	-	-	-	-	-	14.7	-	-	3.8

[a] Case I values extrapolated from CASE III test data.

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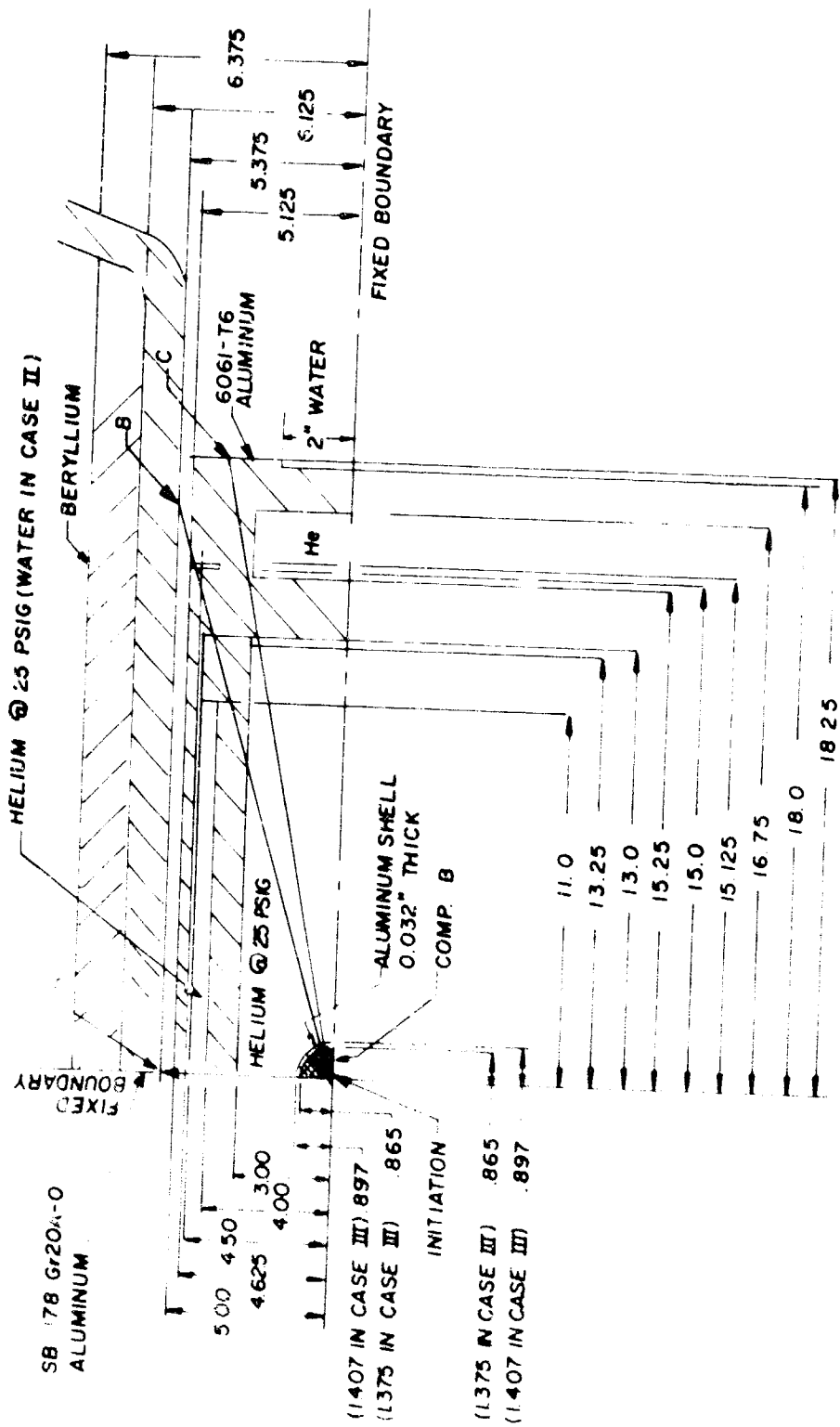
Fig 14 Two-dimensional model of capsule with dimensions and materials

45
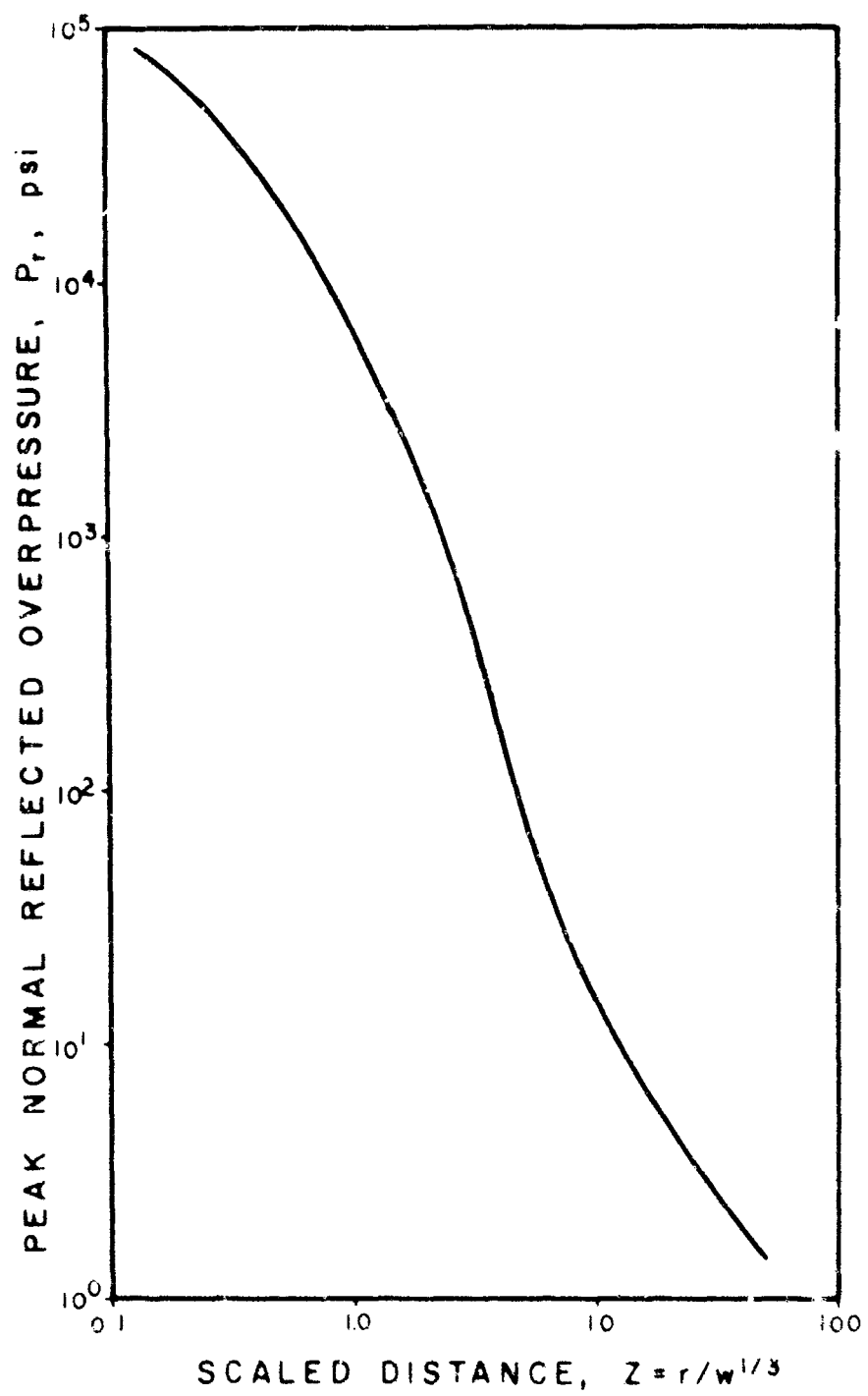
Fig 16   Curve for peak reflected overpressure
versus scaled distance.   TNT spherical
charge pressure-versus-distance scaling
law.
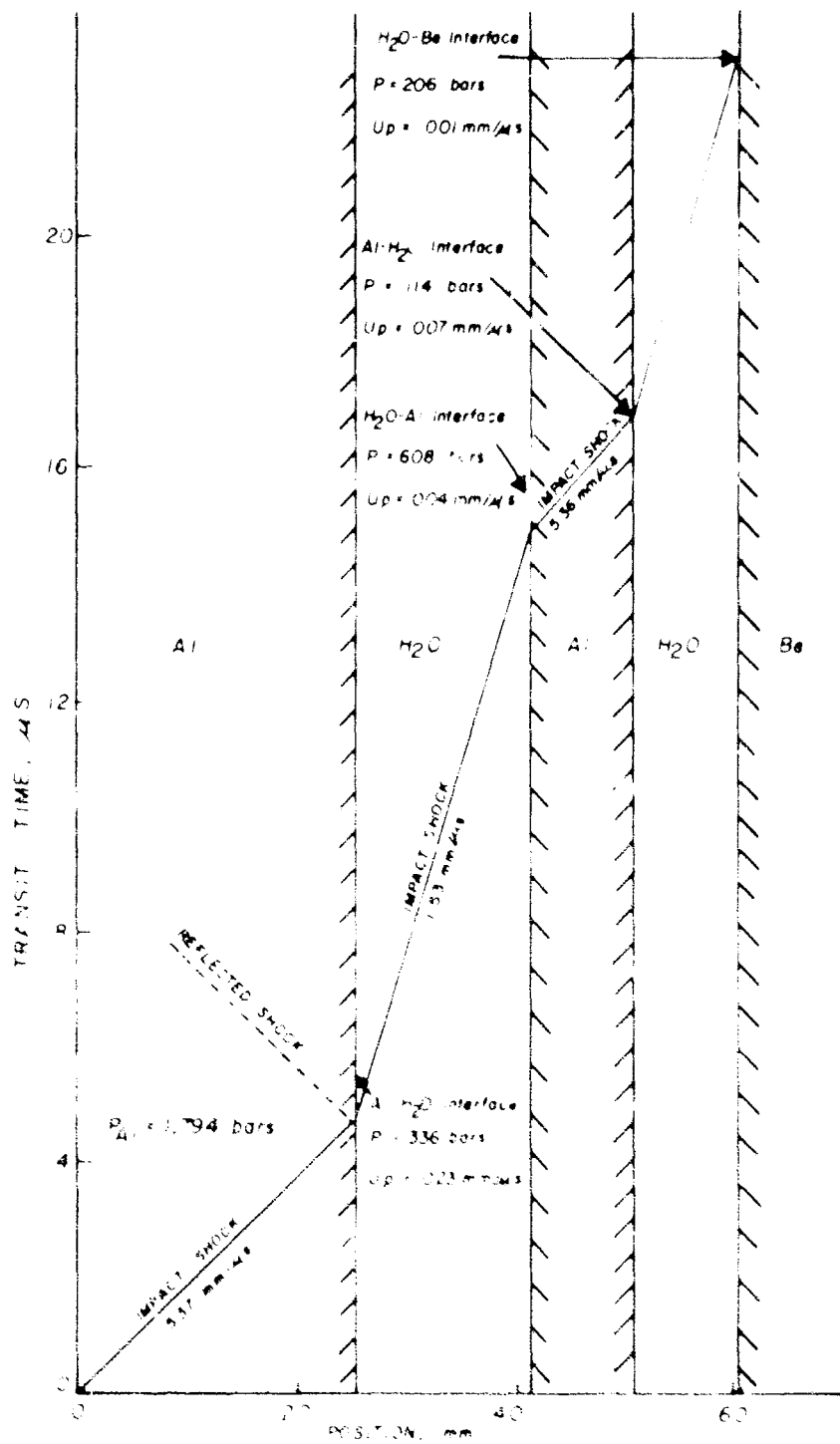
46

Fig. 16 — ... shock ... interface ...

Fig 17   LRL K.O. input geometry

Labels on diagram (outer to inner):
- Beryllium
- Aluminum
- Water
- Aluminum
- Helium or Water
- Aluminum
- Helium
- Aluminum
- Composition B Explosive

Dimensions: 6.36, 6.125, 4.50, 5.375, 4.00, 5.00, 3.00, 1.40, 1.375
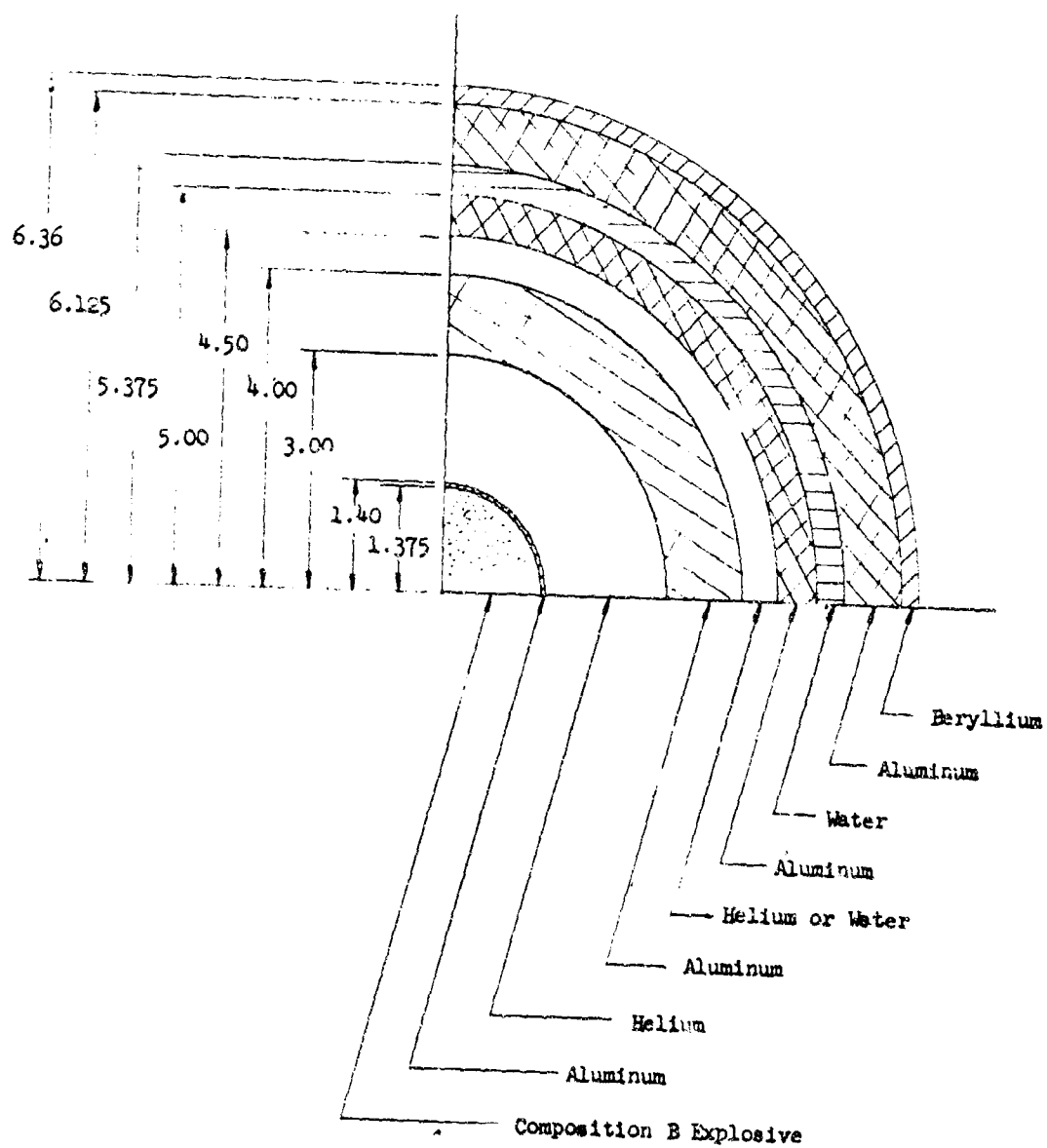
Metal	Shear Modulus	Yield Strength	Density, g/cc
Be	17.65×10^{6} psi	14,700 psi	1.84
Al	364.5×10^{6} psi	44,100 psi	2.70

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TABLE 6

LRL K.O. Computer Code Results

Case	Description	Max Pressure in Water		Max Tensile Strain in Beryllium	
		Psi	Time After Detonation μsec	μin./in.	Time After Detonation μsec
III-A	160-gram charge, helium in annulus, round-off pressure at 10^{-9} megabars	14.7	130	48.2	145
III-A	Same as above but no rounding off of pressures	23.2	125	53.3	150
IV-A	160-gram charge, water in annulus, round-off pressure at 10^{-9} megabars	3.78	150-165	20.1	175

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An additional calculation was made by LRL in which
160 grams were detonated with the annulus filled with
water so that a comparison could be made. Making this
very simple change in the code was easier than repeat-
ing the calculations with the 80-gram charge. This is
denoted as Case IV in Table 5. The shock pressures
transmitted or propagated through the water in the
annulus were expected to be higher than those through
helium; however, the LRL calculated pressures were
lower. The indications are, therefore, that this
method of calculation is not accurate at low pressures.
The Picatinny and Aerojet calculations did show that the
pressure pulses would be higher with the water-filled
annulus than with the helium-filled case.

Although peak shock pressures as high as 100,000
psi were calculated by Aerojet for the water-filled
case, as compared to 3000 psi for Picatinny, these were
not expected to cause any permanent deformation or
damage to the reactor components because of the absence
of permanent strain reported in the LRL calculations.
This was confirmed in the Aerojet small-capsule tests
where a peak pressure of 74,000 psi produced no perma-
nent deformation of the mock-up of the trail cable tube
less than one inch away. For irradiation the Z trail
cable tube assembly of the General Electric Test Re-
actor was used for insertion of the small capsules into
the reactor irradiation location. Also, qualitative
tests showed that this pulse moving at velocities rang-
ing from 120 to 340 meters per second would not break a
0.0008-inch-thick aluminum foil immersed in water 7
inches away or break a 150-watt light bulb 19 inches
away (Ref 4). Indications are that the high-order deto-
nation of an explosive sample in the small capsule dur-
ing an actual irradiation in the reactor did not affect
the surroundings.

Table 5 summarizes the calculations made by the
three groups and also includes a grouping of the ex-
perimental data from Table 3. As the table indicates,
the Picatinny calculations were in closer agreement
with the measured test data than the values calculated
by Aerojet or Lawrence Radiation Laboratory. The Pica-
tinny calculations show a 40% decrease in peak shock
pressure when the weight of the explosive charge was
reduced from 160 to 80 grams. This ratio was used to

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predict the extrapolated test values shown in Table 5
that would be observed if 80 grams were detonated with
a helium filled annulus.

Good agreement is shown with Positions A and C.
The difference of an order of magnitude with respect to
the values in Position B is probably due to the oblique-
ness of the shock without considering any reflections
in what is almost a two-dimensional corner.

The measurements of the peak pressure at Position
C should be analogous to those of the water-filled
radial gap. Since the shock propagates through aluminum
the pressure would be higher; conversely, the distance
from the explosive charge to the capsule corner is
greater than the radial distance, tending to lower the
calculated pressure in accordance with the scaling law.

The experimental data also indicated that all the
shock pressures measured were of low energy content
since the pulse durations or pulse widths were 20 micro-
seconds or less. The time intervals and the tensile
stresses calculated by LRL seem to agree with the shock
arrival times in Table 4 and the strain measurements
in Table 3.

This brings up the point as to the type of waves,
either shock or sound, that are actually emanating from
the containment capsule. It should be noted that in
the pressure profile of a sound wave the pressure dif-
ference between any two successive points is infinitesi-
mal, implying that the pressure profile in a sound wave
is continuous. A finite difference at any point is a
discontinuity and denotes a shock wave. In a sound
' ve, the medium merely vibrates and passes its energy
on to the next layer. In a shock wave the material
moves physically in the direction of advance of the
pulse. Another way of saying this is that in a sound
wave the material transport averages zero whereas in a
shock wave it is greater than zero. This explains why
the walls of the aquarium did not collapse during the
testing.

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CONCLUSIONS AND RECOMMENDATIONS

In summary it can be stated that the major problems in the design and development of a large explosive containment irradiation capsule have been solved and that an 80-gram sample can be irradiated safely. Through engineered safeguards and conservative approaches, with a minimum safety factor of two, the integrity of the capsule can be maintained if an explosion occurs, a controlled release of the gaseous products can be achieved, and any pressure pulse emanating from the container will have been reduced to such a degree as to preclude any adverse effect on the surrounding medium.

The safe operation of the nuclear reactor is still the responsibility of the nuclear safety group and the operating management. Qualified approval for the capsule has been given. Nevertheless, further clarification or study is needed to eliminate the persistent doubt as to whether the reactor will be affected by any low pressure pulses that would be transmitted by the capsule should a detonation occur. The engineered safeguards, precautions, and safety factors were incorporated in the design, development, and operation of the explosive containment irradiation capsule to prevent the "credible" accident with the worst consequences but the doubt still persists. The solution can be approached in either of two ways:

1. Conduct dynamic loadings on reactor components or equivalent to the maximum obtained in tests.

2. Incorporate an additional or wider annular gap in the capsule or an equivalent shield between the capsule and reactor to completely attenuate any pressure pulse.

Further study should be conducted on computer calculations, which would predict accurately the pressures, stresses, and strains, and the time references for each.

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APPENDIX I

Detail Drawings for Phase II Explosive
Container for Reactor Irradiation,
Including Concept for Rail Cable Fixture
for Inserting and Locating the Explosive
Container in the General Electric Test Reactor

APPROVED SOURCE

◄ CONAX CORP
BUFFALO, NY

◄ IMPERIAL EASTMAN CO
6300 W HOWARD ST
CHICAGO, ILL, OR EQUAL

◄ ELECTRICAL INDUSTRIES
691 CENTRAL AVE
MURRAY HILL, N J

◄ FLEXITALIC GASKET CO
5 LINDEN ST
CAMDEN, 2, NJ

◄ CAJON
32550 S OLD MILES RD
SOLON 39 OHIO OR EQUAL

◄ CONAX MANN METAL 4 SUPPLY
LOS ANGELES, CALIFORNIA

BILL OF MATERIAL

NOMENCLATURE
(COMMERCIAL ITEMS)

QN ZN		NOMENCLATURE	
1	2	CONNECTOR, 2 WIRE, CONAX MHM-040-A12L	a
2	2	FITTING, STRAIGHT, 37° FLARE, 5/16 TUBING, 1/4 IPS THD, IMPERIAL NO 848-F&S	a
3	3	SOCKET, WELD, MALE CONNECTOR, 5/8 OD TUBE, 1/8 NPT PART NO 2 SW 12 304L	a
4	4	PIPE, 1, 3, 1/8 NPT, PART N 2 F 304L	a
5	5	SEAL, GLASS TO METAL, 12 TUBES (PINS), TYPE 125 SFR / 20T-RR-P-2E	c
6	SOFT	TUBING, 5/16 OD x 035 WALL, ALUMINUM, 6061-T4 (ALUMINUM 3050-0 OPTIONAL)	a
7	2	GASKET N° 3065-IPAJ	a
8	AS REQD	SOCKET WELD, UNION, 5/8 OD TUBE PART NO 2 SW 6 304L	a
9	AS REQD	TUBING, TYPE 304 SS, 5/8 OD x 020 WALL	a
10	1	CONNECTOR, 2 WIRE CONAX MHOM AK, (SEE DTA)	a
11	1	REDUCER, 5/8 x 1/2 PS DOUBLE FEMALE, STAINLESS STEEL, TYPE 304 OR 316	b

NOTES

1 ALL HARDWARE (NUTS, BOLTS, SCREWS, ETC) TO BE ALUMINUM
  OR STEEL UNLESS OTHERWISE NOTED

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To Experiment Hoist

Missile Shield

Third Floor Elevation
611ft-7in.

Existing 45° Penetration

Reactor Pool

Track

Elevation
599ft-8-7/8in.

Instrumentation Lea·
to Third Floor Console

Experiment

Experiment Dolly

℄ Core

Elevation
586ft-2-7/8in.
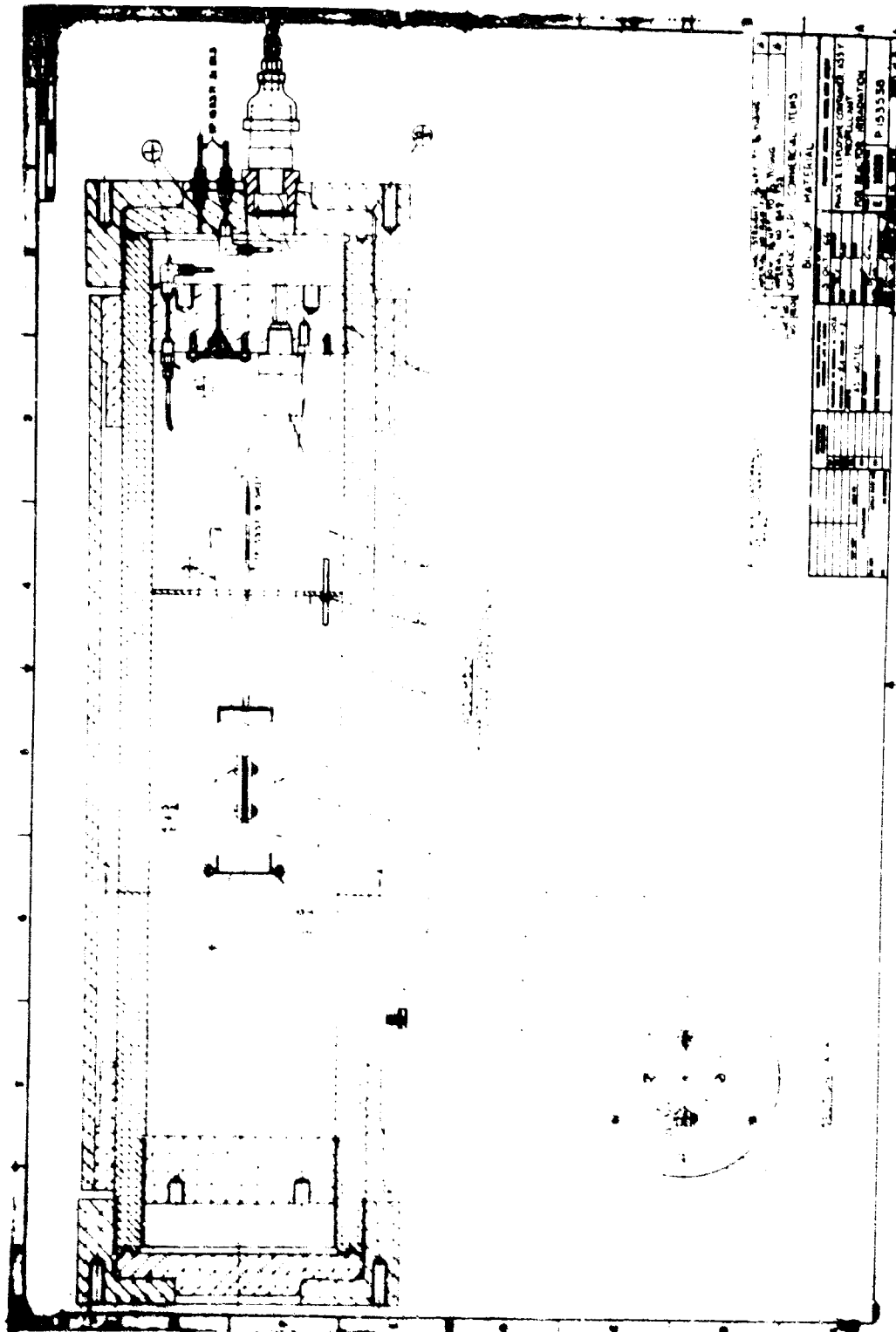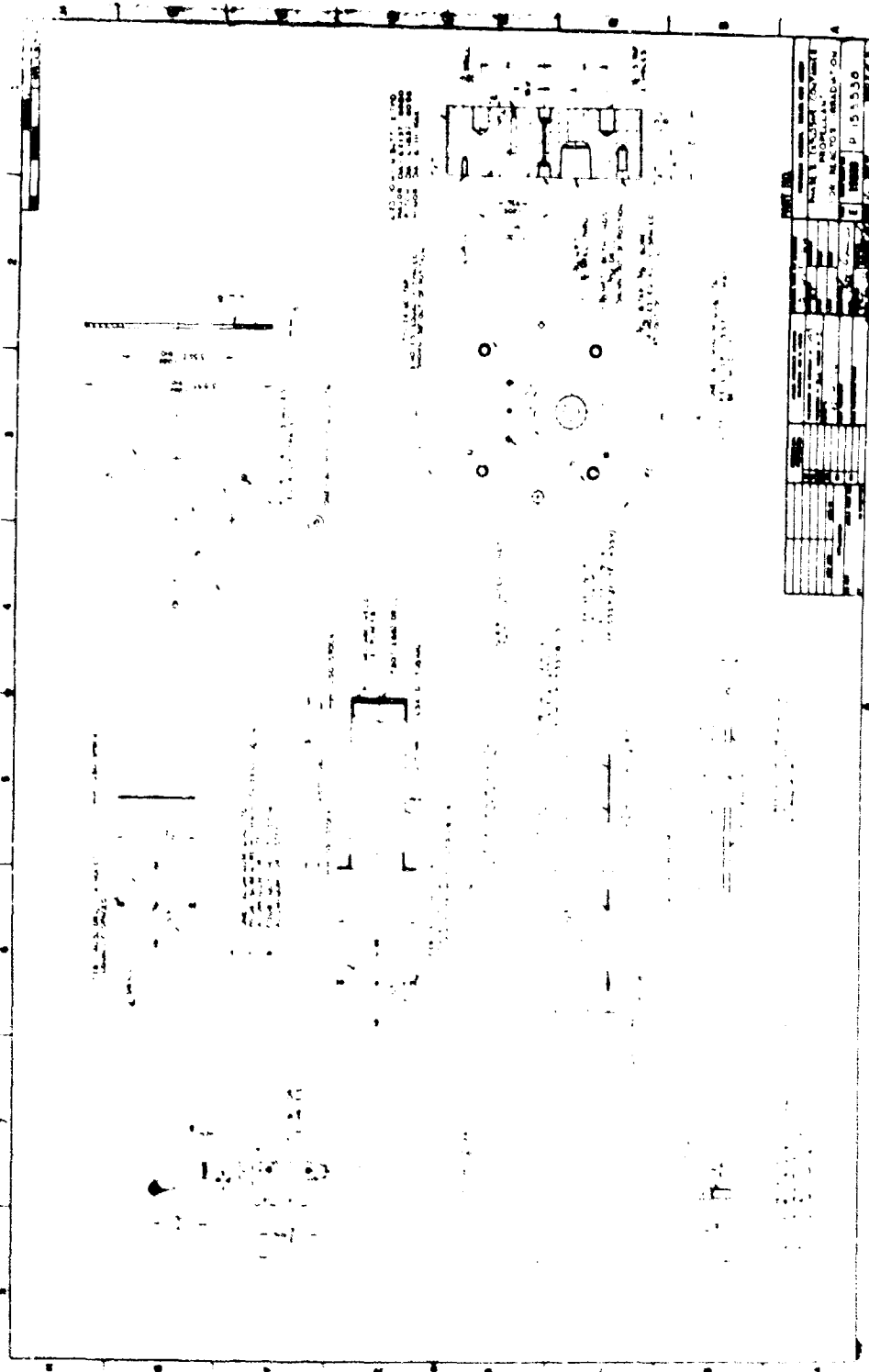
Track Positioning Mechanism
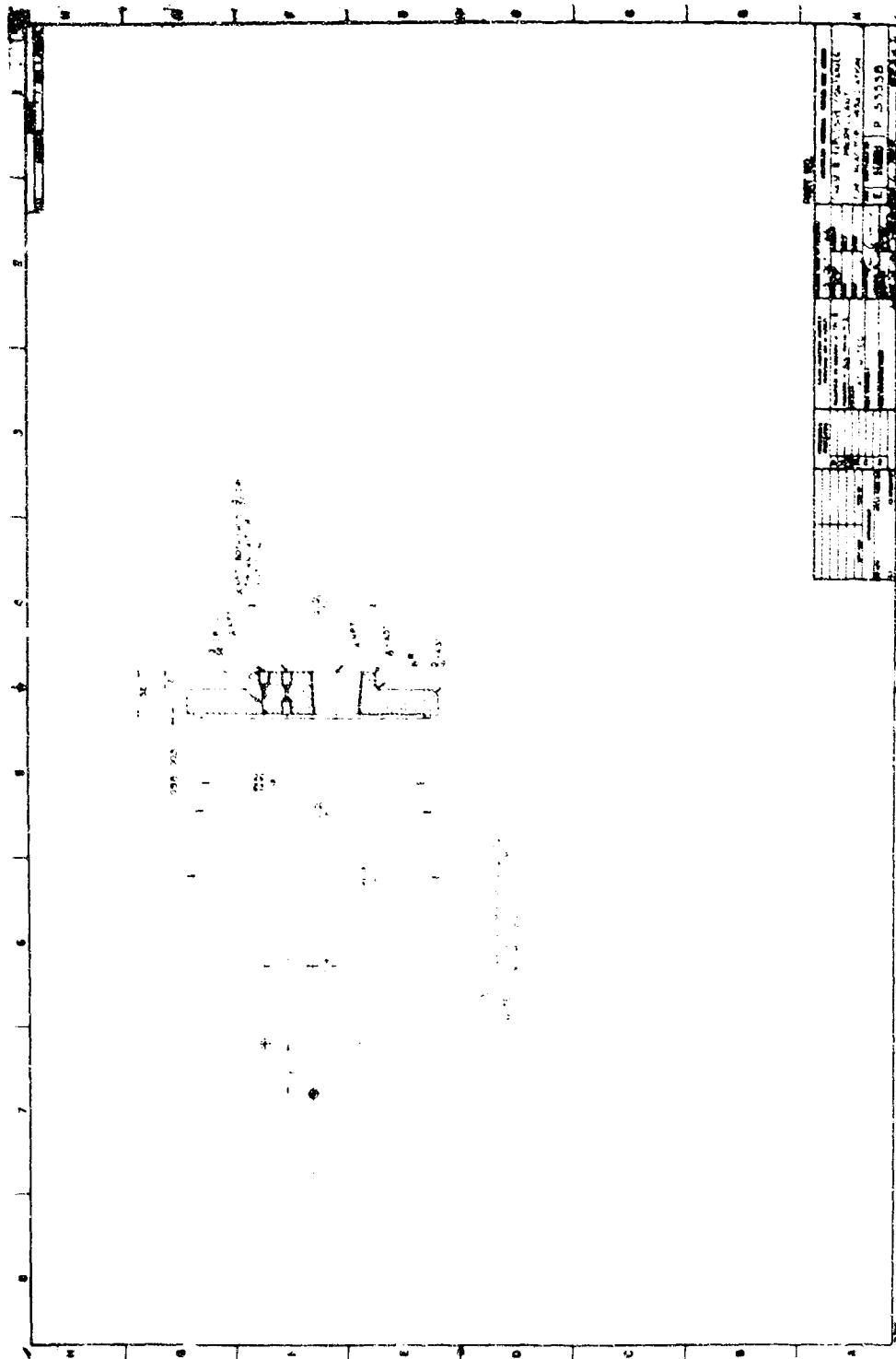
RAIL CABLE FIXTURE

GENERAL ELECTRIC TEST REACTOR

AEROJET GENERAL PHASE II CAPSULE IRRADIATION CONCEPT

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APPENDIX II

Detail Drawings for Phase II Explosive
Container for Reactor Irradiation of
Propellants and Detonators (Set of 4)

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DETONATOR CONTAINER

SCALE 1/1, AUG 10 1966
DRAWN PLF (PICATINNY ARSENAL)

MATERIAL: ALUMINUM 6061-T6, BOTH PIECES

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APPENDIX III

One-Dimensional Calculations of Pressure
Pulses Emanating from Phase II Explosive
Containment Irradiation Capsules
Under Certain Conditions

One-dimensional analytical calculations were per-
formed to determine the pressure pulses at various
preselected interfaces noted as points A, B, and C on
the explosive containment irradiation capsule. These
points are shown on the two-dimensional model in
Figure 14 in the main body of this report.

In any calculations, certain assumptions must be
made to facilitate the mechanics of the calculations
and to extrapolate the data from known geometries to
those under study. For the work covered in this Ap-
pendix, the following assumptions were made:

1. That the scaling laws wherein the pressure
Pr at any distance from a spherical charge can be re-
lated to the scaled distance Z from the center of the
charge. Also

$$Pr_{TNT} \cong Pr_{Comp\ B}$$

2. That the pressure pulses are approximated
by square waves whose durations are longer than the
transit times (unattenuated shocks).

3. That low pressures can be approximated by
a linear function of the particle velocity $P = ku_p$.

The purposes of these analytical calculations
were to predict the peak shock-pressure pulse emanat-
ing from the explosive containment capsule due to the
detonation of an 80-gram charge should the annulus
fill with water, and to obtain a comparison with ex-
perimental data to determine the accuracy of the
methods of calculation.

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Case I

The central sphere contains 80 grams of Comp B explosive (.865 inch radius at 1.8 g/cm^3) with annular space filled with helium at 25 psig.

> For Comp B, W = 80 g = .176 lb
> ID of containment vessel = 6 inches

The pressure incident on the chamber wall is based on the calculated reflected overpressures Pr with the provision as noted that TNT $\simeq$ Comp B (Ref 1).

Position A (Case I)

$$W^{1/3} = .56 \ lb^{1/3}$$

Y^1 = .25 foot distance from center of charge to wall collinear with point A

$$Z = \frac{Y^1}{W^{1/3}} = \frac{.25}{.56} = .446 \ ft/lb^{1/3} \ \text{scaled distance}$$

From the curve for spherical charge of TNT (Fig 2.14 in Reference 1; Fig 15 is a portion of that curve)

> P_r = 26,000 psi $\simeq$ 1794 bars
> Assuming P_{Al} = 1.54 $u_{P_{Al}}$

where P_{Al} is pressure in megabars and $u_{P_{Al}}$ is particle velocity in cm/μsec

$$u_p = 1.242 \times 10^{-3} \ cm/\mu sec = .0124 \ mm/\mu sec$$

From U_{Al} = .533 + 1.34 $u_{P_{Al}}$

where U_{Al} is shock velocity

$$U_{Al} = 5.37 \ mm/\mu sec$$

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Transit time t for shock through 25.4 mm of aluminum, assuming no attenuation of a square wave pulse

$$t_{Al} = 4.73 \ \mu sec$$

From scaled impulse curve (Ref 1)

$$\frac{I_r}{W^{1/3}} = 1250 \ \frac{lb\text{-}ms}{in.^2\text{-}lb^{1/3}} \text{ from which } I_r = 700 \ lb\text{-}ms$$

$$I_r = \int_{t_1}^{t_2} P \ dt = P(t_2 - t_1)$$

$$\text{or } \Delta t = \frac{I_r}{P} - .027 \ ms = 27 \ \mu sec$$

Assuming a square wave pulse of 27 μsec duration, pressure pulse Pr should be transmitted through 25.4 mm of Al unattenuated. Moreover, from P versus u_p curve for aluminum, since the subsequent interface is between Al and He, and since He is a highly compressible gas, the pressure at that interface will approach 0 and the particle velocity u_p would double ($u_p \cong .0248 \ mm/\mu sec$). There $P_A \cong 0$ for position A in case 1.

Position B (Case I)

A point on the inner chamber wall collinear with both the center of the charge and position B would lie 10 inches from the center of the charge.

$$Y^1 = 10 \text{ inches or } .82 \text{ foot}$$

$$Z = \frac{Y^1}{W^{1/3}} - 1.46 \ ft/lb^{1/3} \text{ scaled distance}$$

From the curve for TNT charge (Fig 2.14, Ref 1)

$$Pr = 3250 \text{ psi} \simeq 224 \text{ bars}$$

$$U_{Al} \simeq .535 \text{ cm/usec (roughly sonic)}$$

$$u_p = 1.55 \times 10^{-4} \text{ cm/usec}$$

Moreover, since this is an oblique shock in relation to the vessel wall, calculations assuming normal incidence would be much higher than the actual value. Such calculations give a value of 26 bars or 370 psi, which can be considered as an upper limit. For position B (case I) the calculations indicate that the pressure pulse > 370 psi.

Position C (Case I)

$$W1/3 = .56 \text{ lb}1/3$$

$Y^1 = 1.13$ feet distance from center of charge to wall collinear with position C.

$$Z = \frac{Y^1}{W^{1/3}} = 2.02 \text{ ft/lb}^{1/3} \text{ scaled distance}$$

From the curve for TNT (Fig 2.14, Ref 1)

$$Pr = 1600 \text{ psi} \simeq 110 \text{ bars}$$

$$U_{Al} \simeq 5.35 \text{ mm/usec}$$

Transit time t for shock through 127.0-mm wall

$$t_{Al} = 23.7 \text{ usec}$$

From scaled impulse

$$\frac{I_r}{W^{1/3}} = \frac{120 \text{ lb-ms}}{\text{in.}^2 \text{-lb}^{1/3}} \quad I_r = 67.2 \text{ lb-ms}$$

$$\Delta t = .042 \text{ ms} = 42 \text{ usec}$$

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Assuming a linear relation between P and u_p at low pressures

$$P_{Al} \cong 1.445 \, u_{P_{Al}}, \text{ and } P_{H_2O} \cong .148 \, u_{P_{H_2O}}$$

Using the reflected curve technique for equating pressures and particle velocities at an interface.

Reflected curve for $P_{Al} = -1.445 \, u_{P_{Al}} + 2.20 \times 10^{-4}$

where at

$$P_{Al} = 0, \quad u_{P_{Al}} = 2(.76 \times 10^{-4})$$

$$P_{Al} = 1.10 \times 10^{-4} \text{ megabars}$$

$$\text{at } u_{P_{Al}} = .76 \times 10^{-4} \text{ cm/}\mu\text{sec}$$

$$P_{Al} = -1.445 \, u_{P_{Al}} + 2.20 \times 10^{-4}$$

$$P_{H_2O} = .148 \, u_{P_{H_2O}}$$

$$1.593 \, u_p = 2.20 \times 10^{-4}$$

$$u_{P_{Al-H_2O}} = 1.38 \times 10^{-4}$$

$$P_{Al-H_2O} = .204 \times 10^{-4} \text{ megabars}$$

Therefore P at interface $\cong$ 20.4 bars or 296 psi for position C (case I).

Case II

Same as case I except annular space filled with water.

Position A (Case II)

$Z = .446$ and $Pr = 26,000$ psi $= 1794$ bars (of case I, position A).

Assuming that pressures are linear functions of particle velocities, then

$$P_{Al} \cong 1.445 \, u_{P_{Al}}$$

$$P_{H_2O} \cong .149 \, u_{P_{H_2O}}$$

$$P_{Be} \cong 1.435 \, u_{P_{Be}}$$

Using the reflected curve technique (graphical) for matching pressures and velocities at the various interfaces:

At 1st interface, Al-H_2O

$$P_{Al} = -1.445 \, u_{P_{Al}} + 3.59 \cdot 10^{-3} \quad \text{(reflected curve for Al)}$$

$$P_{H_2O} = .149 \, u_{P_{H_2O}}$$

$$1.594 \, u_{P_{Al-H_2O}} = 3.59 \times 10^{-3}$$

$$u_{P_{Al-H_2O}} = 2.251 \cdot 10^{-3} \, cm/.sec$$

$$P = 335.7 \, bars$$

At 2nd interface, H_2O-Al

$$P_{H_2O} = -.149\ u_{P_{H_2O}} + 6.7 \times 10^{-4} \quad \text{(reflected curve for } H_2O\text{)}$$

$$P_{Al} = 1.445\ u_{P_{Al}}$$

$$1.594\ u_P = 6.7 \times 10^{-4}$$

$$u_{P_{H_2O\text{-}Al}} = 4.21 \times 10^{-4} \text{ cm/}\mu\text{sec}$$

$$P = 608 \text{ bars}$$

At 3rd interface, Al-H_2O

$$P_{Al} = 1.445\ u_{P_{Al}} + 1.216 \times 10^{-3}$$

$$P_{H_2O} = .149\ u_{P_{H_2O}}$$

$$1.594\ u_{P_{Al\text{-}H_2O}} = 1.216 \times 10^{-3}$$

$$u_{P_{Al\text{-}H_2O}} = .736 \times 10^{-3} \text{ cm/}\mu\text{sec}$$

$$P = 113.7 \text{ bars}$$

At 4th interface, H_2O-Be

$$P_{H_2O} = .149\ u_{P_{H_2O}} + .227 \times 10^{-3}$$

$$P_{Be} = 1.435\ u_{P_{Be}}$$

$$1.584\ u_{P_{H_2O\text{-}Be}} = .227 \times 10^{-3}$$

$$u_{P_{H_2O}} = 1.43 \times 10^{-4} \text{ cm/}\mu\text{sec}$$

$$P = 206 \text{ bars}$$

Position A, case II is graphically depicted in Figure 16. It has been assumed that the incoming pressure pulse is 1794 bars and that the associated impact shock passes through the various media unattenuated (square pressure pulse). It is further assumed that because of the low shock velocities through the various media the reflected shocks would not appreciably reinforce the primary impact shocks because of the long transit times involved. For Position A (case II) the pressure pulse would be P = 206 bars = 2987 psi.

Positions B and C (Case I)

Positions B and C would be the same as those for case I, since the geometries are identical. Therefore for position B (case II), P = 370 psi, and for position C (case II), P = 296 psi.

Case III

Central sphere contains 160 grams of Comp B explosive (1.375 inches radius at 0.9 g/cm^3), annular space filled with helium at 25 psig.

$$\text{For Comp B, } W = 160 \text{ g at } \rho = 0.9 \text{ g/cm}^3$$

Position A (Case III)

The deduced pressure Pr is based on the scaled distance Z which considers only the total mass of the explosive; the density of the charge does not appear in any of the calculations

$$Z = \frac{r^1}{W^{1/3}} = \frac{.25}{.352^{1/3}} = .354 \text{ ft/lb}^{1/3}$$

From curve for spherical TNT charge (Ref 1)

$$Pr = 34,000 \text{ psi} = 2,346 \text{ bars}$$

$$u_p = 1.52 \times 10^{-2} \text{ mm/}\mu\text{sec}$$

$$U_{Al} = .537 \text{ cm/}\mu\text{sec}$$

Moreover the pressure at position A should be $\gtrsim 0$ for the same reason as in case I (see above).

Position B (Case III)

Considering a point on the inner chamber wall collinear with the center of the explosive charge and position B, this point would experience an oblique shock with a peak pressure of 5200 psi at a distance approximately 10 inches from the center of the charge. This linear path up to position B encompasses aluminum, water, aluminum, water, and beryllium. An analysis using pressure and particle velocities at the interfaces assuming normal rather than oblique pressure pulses gives a value of 41 bars of approximately 600 psi. This value will only be obtained under the most adverse of conditions. The true value should be less than this. Therefore for position B (case III) $P > 600$ psi.

Position C (Case III)

Assuming a linear distance from the center of the charge to the wall in the vicinity of point C as 13.6 inches

$$r^1 = 13.6 \text{ inches} = 1.13 \text{ feet}$$

$$Z = \frac{r^1}{W^{1/3}} = 1.60$$

From the curve for TNT,

$$Pr = 2650 \text{ psi or } 183 \text{ bars}$$

$$u_p = 1.27 \times 10^{-4} \text{ cm/}\mu\text{sec}$$

$u_p \gtrsim .535$ cm/μsec or close to sonic velocity. Transit time $t = 23.7$ μsec for 127 mm wall, assuming a square pulse.

As in case I, position C, using the reflected wave technique

$$P_{Al} = -1.445 \, U_{P_{Al}} + 3.67 \cdot 10^{-4}$$

$$P_{H_2O} = .149 \, u_{P_{H_2O}}$$

$$1.594 \, U_{P_{Al-H_2O}} = 3.67 \cdot 10^{-4}$$

$$U_{P_{Al-H_2O}} = 2.3 \cdot 10^{-4} \text{ cm/}\mu\text{sec}$$

$$P = 34 \text{ bars} \approx 500 \text{ psi}$$

Therefore, for position C (case III) the pressure pulse is approximately 500 psi.

The assumption of a linear relationship between pressure and particle velocity at low pressures is based on the following considerations

$$P = \rho U_s u_p \qquad\qquad (1)$$

where

P = pressure

ρ = density

U_s = shock velocity

u_p = particle velocity

For most metals the shock velocity U_s is a linear function of the particle velocity, $U_s = a + b \, u_p$ (Ref 5).

Substituting for U_s in Equation 1

$$P = \rho u_p \, (a + u_p) \qquad\qquad (2)$$

At low pressures or shock velocities the contribution
of the second term is so small that it can be neglected

$$P \simeq \rho a \ U_p \qquad (3)$$

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13. ABSTRACT

The design and development of a large explosive containment cap-
sule for the irradiation of up to 80 grams of explosive materials is
described. The capsule will fully protect its surroundings, e.g.,
the core of a nuclear reactor, if its explosive content detonates.
The minimum safety factor of two was used. The capsule contains pro-
visions for the containment of gases produced by detonation or burn-
ing of the explosive material and the minimizing of any shock wave
propagated outside the capsule. Also, provisions are made to monitor
pressure or gas evolution and the temperature of the test material
during irradiation. Dynamic pressure pulse and stress-strain measure-
ment tests were conducted and are described. Analytical calculations
were made for comparison with experimental data, first to determine
the validity of the calculations and then to obtain information on
configurations not actually tested.